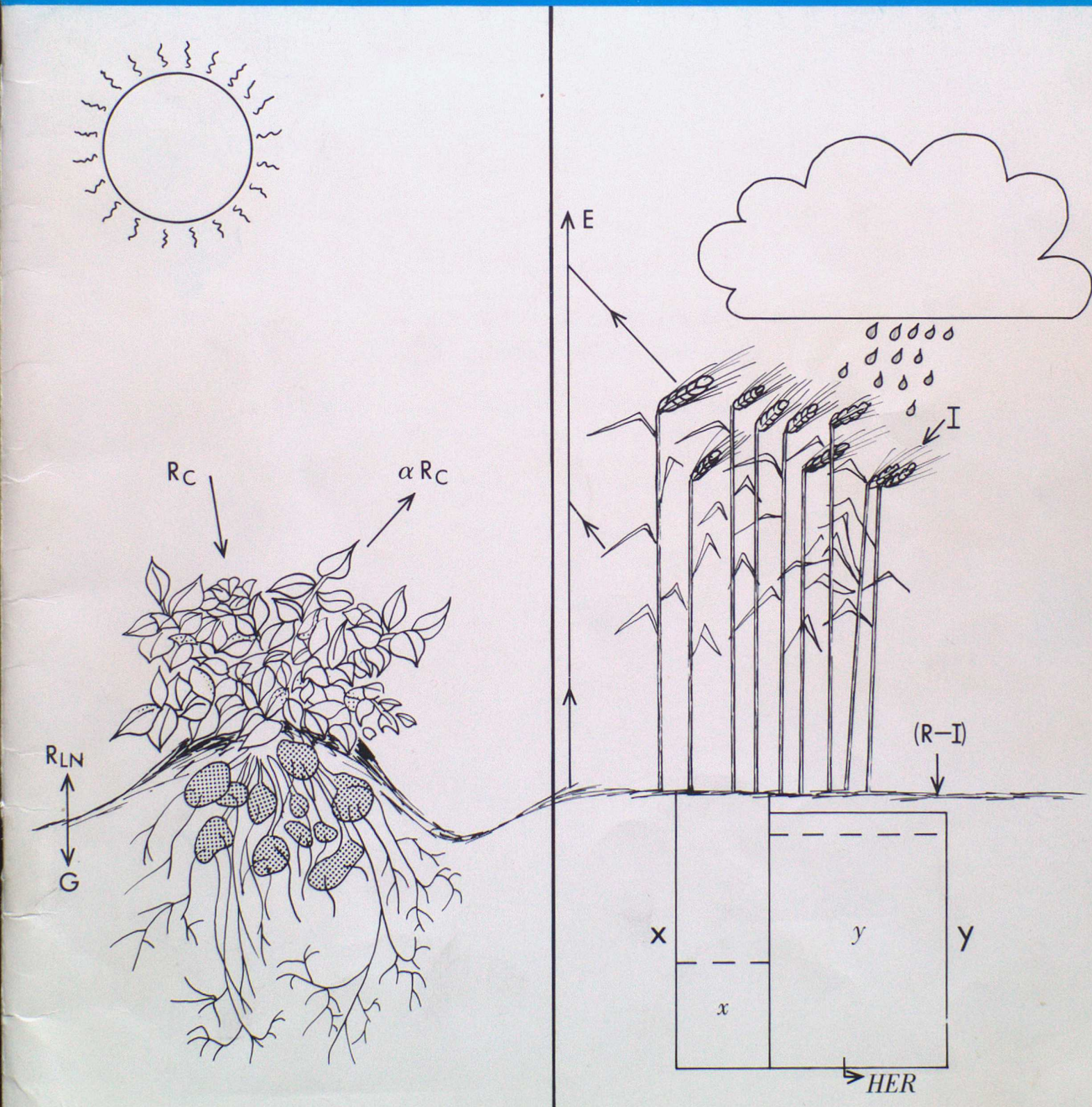
Hydrological Memorandum No. 45

The Meteorological Office Rainfall and Evaporation Calculation System MORECS (July 1981)



LHARVEY

Hydrological Memorandum No. 45

The Meteorological Office rainfall and evaporation calculation system: MORECS (July 1981)

by N. Thompson, I.A. Barrie and M. Ayles

Met O 8 (Hydrometeorological Services)
1981

CONTENTS

		Page
1.	Introduction	1
2.	Purpose of MORECS	2
3.	Outline of MORECS	3
4.	Detailed description of the system	3
4.1	Data collection, averaging and interpolation	3
4.1.1	Data collection: the network of stations and form of data storage	3
4.1.2	Method of averaging data	3
4.1.3	Interpolation of daily average station data to MORECS square estimates	10
4.2	Data analysis to obtain evaporative demand over each grid square	11
4.2.1	Introduction	11
4.2.2	The basic calculation of evapotranspiration: the Penman - Monteith equation	12
4.2.2.1	Available energy: short and long - wave radiation, the effects of cloud, soil heat flux	15
4.2.2.2	Aerodynamic resistance	19
4.2.2.3	Surface resistance when soil moisture is not limiting	23

Page

4.3 Calculation of actual evaporation using a soil moisture extraction model 27

4.3.1 Introduction 27

4.3.2 Relationship between surface resistance and soil moisture deficit 28

4.3.3 Available soil moisture for different crops 30

4.4 Calculation of water balance and excess rainfall 31

4.4.1 Treatment of intercepted water, including condensation 31

4.4.2 Soil moisture deficit and excess rainfall 32

4.4.3 Calculation of real land use values of PE, AE, SMD and HER 33

4.5 MORECS outputs 34

4.6 Comparisons between MORECS outputs and neutron probe data 34

Acknowledgements 36

References 37

Annex A: Dates assumed for crop development 40

Annex B: Estimates of percentage of land use types in each MORECS square 51

Page

Annex C: Examples of MORECS outputs 58

Annex D: Comparison of MORECS and neutron probe data 62

Annex E: Summary of changes to MORECS since its introduction in 1978 72

THE METEOROLOGICAL OFFICE RAINFALL AND EVAPORATION CALCULATION SYSTEM : MORECS (JULY 1981)

by N Thompson, I A Barrie and M Ayles

1. INTRODUCTION

MORECS (an acronym for Meteorological Office Rainfall and Evaporation Calculation System) was introduced in 1978 as an eventual replacement for the Estimated Soil Moisture Deficit (ESMD) bulletin first issued by the Office about 15 years earlier. MORECS has undergone a number of changes since its introduction and was extensively revised in the winter of 1980/81, taking account of lessons learnt in the first years of operation of the system. It is expected to run without major changes in the foreseeable future so it is appropriate to provide now, for users and others interested, an extended description of the current version of the scheme. The description appears in the remaining sections of this Memorandum, and is sufficiently detailed to allow the reader to construct a similar scheme to run on his own computer. Listings of MORECS's present computer program are not provided in this Memorandum, in part for commerical reasons, but also because the data bases which the operational version of MORECS requires are peculiar to the Meteorological Office computer system at Bracknell.

2. PURPOSE OF MORECS

MORECS has been designed to provide estimates of weekly and monthly evaporation and soil moisture deficit in the form of averages over 40 x 40 km grid squares each superimposed over Great Britain, using daily synoptic weather data as its inputs. The outputs assist hydrologists and agriculturalists in a variety of ways; for example in the assessment of catchment water balance and river flow, leaching of nutrients, and short-term irrigation requirements. A specific requirement is for this information to be available to the user as soon as possible after calculation.

3. OUTLINE OF MORECS

The system has five main components (Table 3.1).

Table 3.1 The components of MORECS

1.	Data collection, interpolation and averaging
2.	Data analysis to obtain evaporative demand over each grid square
3.	Calculation of actual evaporation using a soil moisture extraction model
4.	Calculation of water balance and excess rainfall
5.	Data output

The first is the daily extraction from the Synoptic Data Bank at Bracknell of values of meteorological variables which are sometimes called the Penman variables (sunshine, temperature, vapour pressure, wind speed), and rainfall; objective interpolation is then used to obtain grid-square average values of each variable. The next step is the calculation of daily potential evapotranspiration (PE) for each grid square for a range of surface covers from bare soil to forest, using a modified form of the Penman-Monteith combination equation. In the third part of MORECS the PE estimates are converted to estimates of actual evaporation (AE), by progressively reducing the rate of water loss from the potential value to zero as the available soil moisture decrease from 60% of its maximum value to zero. These calculations are made for soils with high, medium and low available water. The next part calculates the daily water balance under the various types of cropped surfaces, and also under the average land use for each square, in this

latter case using the relative proportions of the various surfaces in each grid-square. The final stage is the production of computer-drawn maps showing the grid-square weekly averages of the Penman variables, and also PE, AE, soil moisture deficit (SMD) and excess rainfall (HER, the hydrologically effective rainfall ie run off and aquifer recharge) for grass and real land use. Printouts are also produced showing the same quantities for the individual surface types. Distribution of output is usually by post, but there are limited issues via Telex, facsimile and Prestel.

4. DETAILED DESCRIPTION OF THE SYSTEM

4.1 Data collection, averaging and interpolation

4.1.1 Data collection: the network of stations and form of data storage

The network of stations supplying synoptic data which are used by MORECS is shown in Figure 1, with a list of the required meteorological variables which they report given in Table 4.1.1. Rainfall and sunshine are reported directly as daily totals. The other three variables are usually reported several times each day, though a few stations make observations only once daily, at 0900, when 24-hour maximum and minimum temperatures, and 0900 vapour pressure are recorded. All these data are **available at Bracknell almost immediately after 0900 GMT and are stored in the Synoptic Data Bank (SDB) there.**

4.1.2 Method of averaging data

Daily mean values of air temperature for each station are calculated by averaging observations at 03, 09, 15 and 21**GMT. Where any of these observations** are missing, the daily mean is taken as the average of daily maximum and minimum temperature. Vapour pressure shows relatively small diurnal variations on average (Barrie and Wylie 1980) and is obtained either by averaging observations (at 03, 09, 15 and 21Z) when more than one of these is taken each day, or from the single 0900 value. The daily mean wind speed is calculated as the average of those taken at any of the hours 03, 09, 15 and 21Z observations: the station is used even when only a single observation is available in the 24-hour period. The calculation of daily averages is done each day and the results stored for use in the interpolation routines described below.

Figure 1
Synoptic stations used by MORECS,
17 September 1981

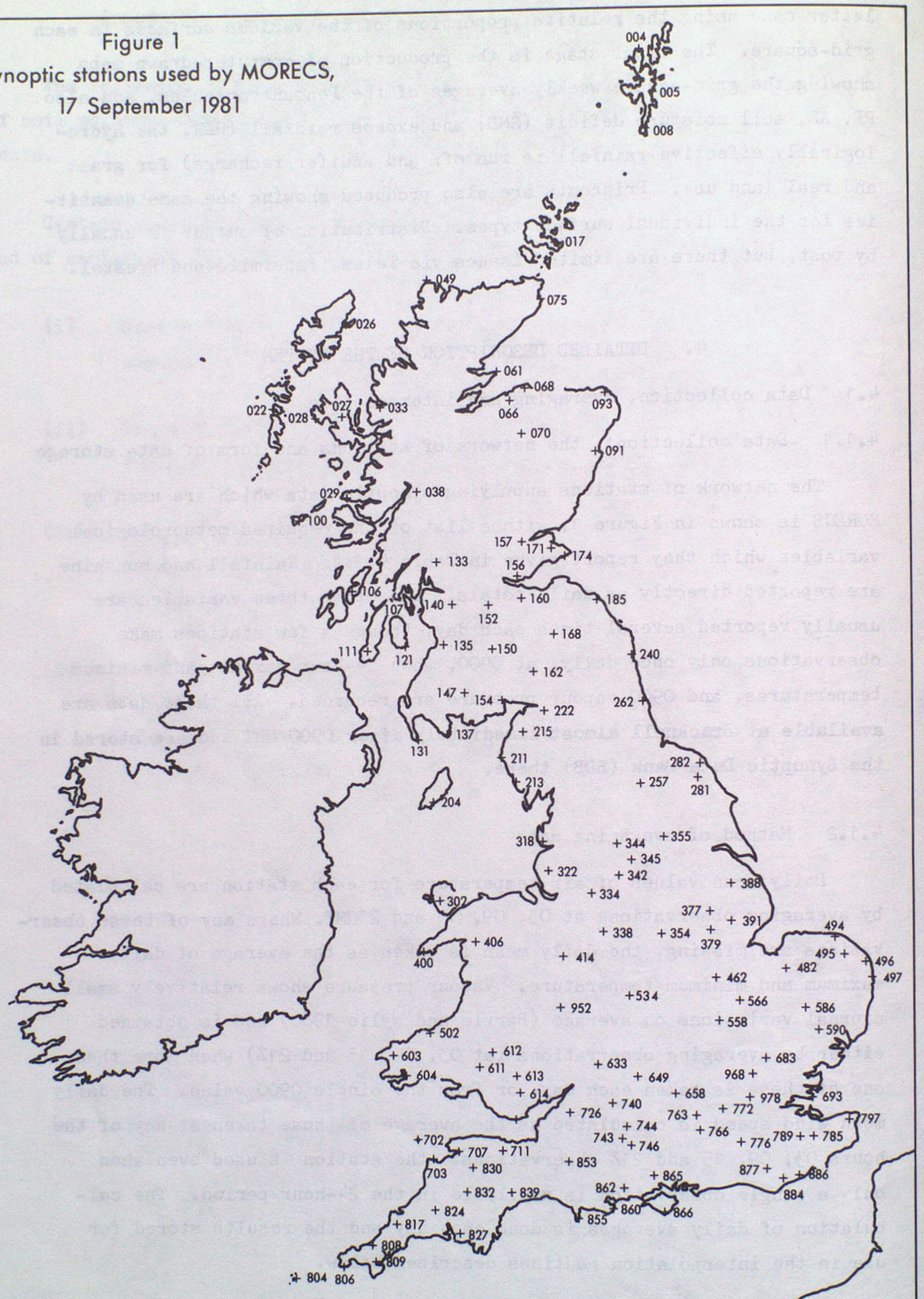


Table 4.1.1

MORECS synoptic stations

STATION	WMO NO	METEOROLOGICAL VARIABLES REPORTED				
		RAIN	SUN	TEMP	WIND	VP
COLLAFIRTH HILL	004	✓		✓	✓	✓
LERWICK	005	✓	✓	✓	✓	✓
FAIR ISLE	008	✓	✓	✓	✓	✓
KIRKWALL	017	✓	✓	✓	✓	✓
BENBECULA	022	✓	✓	✓	✓	✓
STORNOWAY	026	✓	✓	✓	✓	✓
PRABOST	027	✓	✓	✓		
NEIST POINT	028	✓		✓	✓	✓
ARDNAMURCHAN	029	✓		✓		
DIABAIG	033	✓		✓	✓	✓
FORT WILLIAM	038	✓		✓		
CAPE WRATH	049	✓	✓	✓	✓	✓
KINLOSS	066	✓	✓	✓	✓	✓
LOSSIEMOUTH	068	✓		✓	✓	✓
GLENLIVET	070	✓	✓	✓		✓
WICK	075	✓	✓	✓	✓	✓
ABERDEEN/DYCE	091	✓	✓	✓	✓	✓
FRASERBURGH	093	✓		✓	✓	✓
TIREE	100	✓	✓	✓	✓	✓
RHUVAAL	106	✓		✓	✓	✓
DHU LOCH	107	✓		✓		
MACHRIHANISH	111	✓	✓	✓	✓	✓
KILDONAN	121	✓	✓	✓		
MULL OF GALLOWAY	131	✓		✓	✓	✓
SLOY	133			✓		
PRESTWICK	135	✓	✓	✓	✓	✓
WHITHORN	137	✓	✓	✓		
ABBOTSINCH	140	✓	✓	✓	✓	✓
GLENLEE	147	✓		✓		
CRAWFORDJOHN	150	✓		✓		

MORECS synoptic stations

STATION	WMO NO	METEOROLOGICAL VARIABLES REPORTED				
		RAIN	SUN	TEMP	WIND	VP
SALSBURGH	152	✓		✓		
DUMFRIES/DRUNGANS	154	✓		✓		
PITREAVIE	156	✓		✓		
PERTH	157	✓		✓		
TURNHOUSE	160	✓	✓	✓	✓	✓
ESKDALEMUIR	162	✓	✓	✓	✓	✓
GALASHIELS	168					
LEUCHARS	171	✓	✓	✓	✓	✓
ST ABBS HEAD	185	✓		✓		✓
RONALDSWAY	204	✓	✓	✓	✓	✓
ST BEES HEAD	211	✓				
ESKMEALS	213	✓	✓	✓	✓	✓
ASPATRIA	215	✓	✓	✓	✓	✓
CARLISLE	222	✓	✓	✓	✓	✓
BOULMER	240	✓	✓	✓	✓	✓
LEEMING	257	✓	✓	✓	✓	✓
TYNEMOUTH	262	✓	✓	✓	✓	✓
FYLINGDALES	281	✓		✓		
WHITBY	282	✓		✓	✓	✓
VALLEY	302	✓	✓	✓	✓	✓
SQUIRES GATE	318	✓	✓	✓	✓	✓
AUGHTON MET	322	✓	✓	✓	✓	✓
RINGWAY	334	✓	✓	✓	✓	✓
CELLARHEAD	338	✓		✓	✓	✓
HOLME MOSS	342	✓		✓		
WILSDEN	344	✓		✓	✓	✓
EMLEY MOOR	345	✓		✓		
WATNALL	354	✓	✓	✓	✓	✓
CHURCH FENTON	355	✓		✓		
FINNINGLEY	360	✓	✓	✓	✓	✓
WADDINGTON	377	✓	✓	✓	✓	✓

MORECS synoptic stations

STATION	WMO NO	METEOROLOGICAL VARIABLES REPORTED				
		RAIN	SUN	TEMP	WIND	VP
CRANWELL	379	✓	✓	✓	✓	✓
BINBROOK	388	✓	✓	✓	✓	✓
CONINGSBY	391	✓		✓	✓	✓
BARDSEY ISLAND	400	✓		✓	✓	✓
TRAWSFYNYDD	406	✓		✓	✓	✓
SHAWBURY	414	✓	✓	✓	✓	✓
WITTERING	462	✓		✓	✓	✓
MARHAM	482	✓	✓	✓	✓	✓
CROMER	494	✓			✓	✓
COLTISHALL	495	✓		✓	✓	✓
HEMSBY	496	✓	✓	✓	✓	✓
GORLESTON	497	✓	✓	✓		
ABERPORTH	502	✓	✓	✓	✓	✓
CENARTH	504					
ELMDON	534	✓	✓	✓	✓	✓
BEDFORD	558	✓	✓	✓	✓	✓
WYTON	566	✓		✓	✓	✓
HONNINGTON	586	✓	✓	✓	✓	✓
WATTISHAM	590	✓	✓	✓	✓	✓
BRAWDY	603	✓	✓	✓	✓	✓
MILFORD HAVEN	604	✓		✓	✓	✓
BRYNAMMAN	611	✓		✓		
TRECASTLE	612			✓		
CILFYNYDD	614	✓		✓	✓	✓
GLOUCESTER	633	✓	✓	✓	✓	✓
BRIZE NORTON	649	✓	✓	✓	✓	✓
BENSON	658	✓	✓	✓	✓	✓
STANSTED	683	✓	✓	✓	✓	✓
SHOEBURYNESS	693	✓	✓	✓	✓	✓
LUNDY	702	✓		✓		

MORECS synoptic stations

STATION	WMO NO	METEOROLOGICAL VARIABLES REPORTED				
		RAIN	SUN	TEMP	WIND	VP
HARTLAND PT	703	✓	✓	✓	✓	✓
CHIVENOR	707	✓		✓	✓	✓
EXTON	711	✓		✓		
RHOOSE	715	✓	✓	✓	✓	✓
LYNEHAM	740	✓	✓	✓	✓	✓
LARKHILL	743					
UPAVON	744	✓		✓		
BOSCOMBE DOWN	746	✓	✓	✓	✓	✓
SOUTH FARNBOROUGH	766	✓		✓	✓	✓
HEATHROW	772	✓	✓	✓	✓	✓
GATWICK	776	✓	✓	✓	✓	✓
CHARING	785	✓		✓		
ULCOMBE	789	✓	✓	✓	✓	✓
MANSTON	797	✓	✓	✓	✓	✓
SCILLY	804	✓	✓	✓	✓	✓
GWENNAP HEAD	806	✓		✓	✓	✓
CAMBOURNE	808	✓	✓	✓	✓	✓
CULDROSE	809	✓	✓	✓	✓	✓
ST MAWGAN	817	✓	✓	✓	✓	✓
BASTREET	824	✓	✓	✓		
MOUNT BATTEN	827	✓	✓	✓	✓	✓
BURRINGTON	830	✓		✓		
OKEHAMPTON	832	✓		✓		
EXETER	839	✓	✓	✓	✓	✓
YEOVILTON	853	✓		✓	✓	✓
PORTLAND BILL	855	✓	✓	✓	✓	✓
ANVIL POINT	860	✓		✓		
HURN	862	✓	✓	✓	✓	✓
SOUTHAMPTON WEATHER CENTRE	865	✓				
ST CATHERINE'S POINT	866	✓		✓	✓	✓
EAST HOATHLY	877	✓	✓	✓		

MORECS synoptic stations

STATION	WMO NO	METEOROLOGICAL VARIABLES REPORTED				
		RAIN	SUN	TEMP	WIND	VP
HERSTMONCEUX	884	✓	✓	✓	✓	✓
FAIRLIGHT	886	✓		✓	✓	✓
Recent additions						
TARBETNESS	061	✓		✓	✓	✓
FIFE NESS	174	✓		✓	✓	✓
MERTHYR TYDFIL	613	✓		✓		
BRISTOL WEATHER CENTRE	726	✓		✓	✓	✓
BRACKNELL/BEAUFORT PARK	763	✓	✓			
Stations received by telex specifically for MORECS	MORECS No.					
LUDLOW	952	✓				
STANSTEAD ABBOTS	968	✓				
COPPER MILLS	978	✓				

4.1.3 Interpolation of daily average station data to MORECS square estimates

The station data are first normalised or standardised as follows:

(i) Rainfall is expressed as a percentage of the annual station average.

(ii) Sunshine is converted to percentage of the average daily duration for the month.

(iii) Temperature and vapour pressure are 'reduced' to sea level, using lapse rates of respectively -0.6 deg C/100m and 2.5%/100m.

(iv) The 10 m windspeed is converted to a value appropriate to a standard site using an empirical factor related to the general terrain roughness around the station.

Interpolation to obtain 40 x 40 km square values is now carried out. First the 9 nearest stations to the centre of each square are selected, irrespective of whether they have data, up to a maximum of 100 km from the centre. However, if there is a station within 0.5 km of the centre then its observations are used alone. Otherwise, from the selected 9 stations there are chosen the 6 nearest with data, but with the proviso that there are no more than 2 stations in each octant. If less than 3 stations are found then an inverse distance squared method of interpolation is used, otherwise plane fitting is carried out (Shearman and Salter 1975).

The grid-square values are then obtained. In the case of rainfall this involves conversion of the percentage value to millimetres using average annual rainfall for the square (1941-70). Similarly sunshine is expressed in hours by using the square-average mean daily duration for the month (1941-70). The interpolated temperatures and vapour pressures are adjusted to the mean altitude of each square. Finally the wind speed values are converted to squares estimates by applying a correction which takes into account the average terrain roughness for the square.

Errors involved in the use of these interpolation procedures are unlikely to be large in the case of temperature and humidity which usually show only slow changes with distance after conversion to sea level. Acceptable estimates of wind speed will also be obtained usually. Greater difficulties are experienced with sunshine. The network of sunshine recorders is fairly sparse, even when both synoptic and climatological stations

are considered and so it is difficult to establish representative long-term daily average values of sunshine duration for the month in each square. This is especially so where the square includes much high ground, because of the paucity of upland measuring sites. For these reasons it is likely that square values of sunshine duration will be overestimated for squares with substantial amounts of high ground. Rainfall shows large spatial variation, even over homogeneous terrain, especially during summer. It is possible to establish fairly reliable long-term average annual rainfall for each square using data from the several thousand rainfall stations. This means that in the very long term the estimates of MORECS square rainfall derived from the limited synoptic rainfall data will be satisfactory. In the shorter term though, such estimates can be misleading, and for this reason it is recommended that those who use MORECS outputs for irrigation scheduling should **install their own rain-gauge.**

4.2 Data analysis to obtain evaporative demand over each grid square

4.2.1 Introduction

Central to MORECS is the scheme used to determine the potential and actual evapotranspiration from the various surfaces which the system considers. Inadequate treatments here are likely to produce systematic errors in calculated evaporation. Corresponding percentage errors in soil moisture deficit will often be larger, since SMD is determined by differences between evaporation and rainfall, with the latter quantities having similar orders of magnitude for much of the year. It is possible to write down physically rigorous equations which will in principle provide very accurate estimates of evaporation. In practice the solution of the equations (to allow for example for the diurnal changes of atmospheric stability) is impossible analytically: the iterative methods which have to be used instead are far too time-consuming for operational use. Simplification is needed therefore and a consequent loss of accuracy. In fact the major errors in a scheme like MORECS arise through shortcomings in the meteorological data-set(§ 4.1.1), and difficulties in specifying the magnitude of the necessary crop physiological variables: errors involved in simplifying the treatment of the physical processes can be made negligible by comparison with the others.

MORECS uses a slightly modified version of the Penman-Monteith equation to calculate directly both potential and actual evapotranspiration, in the latter case adjusting the bulk surface resistance according to the magnitude of the soil moisture deficit. Calculations are done separately for the day and night-time periods, with the daily mean values of wind and temperature being adjusted empirically according to which period is being considered (Barrie and Wylie 1980). The improvement in accuracy gained by following this procedure is small, but it has been adopted in anticipation of possible future use of the night-time results for other operational purposes.

4.2.2 The basic calculation of evapotranspiration: the Penman-Monteith equation

The Penman-Monteith equation provides a rational, physically-based means of calculating water loss from any surface. The equation is

$$\lambda E = \frac{\Delta (R_N - G) + \rho c_p (e_s - e)/r_a}{\Delta + \gamma (1 + r_s/r_a)} \qquad (4.1)$$

where E = rate of water loss (Kg $m^{-2} s^{-1}$)

Δ = rate of change of saturated vapour pressure with temperature (mb $^{o}C^{-1}$)

R_N = net radiation (Wm^{-2}) (+ve downwards)

G = soil heat flux (Wm^{-2}) (+ve downwards)

ρ = air density (Kg m^{-3}) 1·2923 at STP

c_p = specific heat of air at constant pressure (1005 J Kg^{-1})

e_s = saturation vapour pressure at screen temperature (mb)

e = screen vapour pressure (mb)

λ = latent heat of vaporisation ($\simeq$ 2465000 J Kg^{-1})

γ = psychromatic constant (= 0.66 for temperatures in deg C and vapour pressures in mb)

r_s = bulk surface resistance (sm^{-1})

r_a = bulk aerodynamic resistance (sm^{-1})

Direct measurements of R_N are not available for use in MORECS and so R_N has to be estimated using empirical formulae (see § 4.2.2.1).

These formulae assume, inter alia, that the effective surface temperature is equal to screen temperature. This introduces errors, but an attempt to correct them may be made by modifying slightly the Penman-Monteith equation along the lines suggested by Monteith (1981). Thus, one may write

$$R_N = R_{NE} + C \qquad (4.2)$$

where $R_{NE} = R_N$ calculated assuming $T_o = T_{SCR}$

T_o = bulk surface temperature

T_{SCR} = screen temperature

C = correction term

$$= \epsilon\sigma((273.1+T_{SCR})^4 - (273.1+T_o)^4) \qquad (4.2)$$

ϵ = emissivity of surface

σ = Stefan's constant (5.67×10^{-8} Wm^{-2} $^oK^{-4}$)

For small values of $T_{SCR} - T_o$, Eq (4.3) reduces to

$$C \doteq 4\epsilon\sigma (273.1+T_{SCR})^3 (T_{SCR}-T_o)$$

$$= b'(T_{SCR}-T_o) \qquad (4.4)$$

Thus,

$$R_N = R_{NE} + b'(T_{SCR}-T_o) \qquad (4.5)$$

The new combination equation may now be derived. The energy balance at the surface is

$$\lambda E = R_{NE} - G - H - b'(T_o - T_{SCR}) \qquad (4.6)$$

where H = upward flux density of sensible heat from the surface (Wm^{-2})

The resistance equation for this flux density is

$$H = \rho c_p (T_o - T_{SCR})/r_{aH} \qquad (4.7)$$

where r_{aH} = bulk resistance to transfer of sensible heat from its origin at the surface, up to screen height

Similarly

$$E = \rho(q_o - q_{SCR})/(r_s + r_{aE}) \qquad (4.8)$$

where q_o = specific humidity in the substomatal cavities of the surface cover

$\simeq$ saturation specific humidity at bulk surface temperature

r_s = bulk resistance to transfer of water vapour from within the sub-stomatal cavities to (bulk) foliage surface

r_{aE} = bulk resistance to transfer of water vapour from bulk foliage surface up to screen height

Also

$$q_o - q_{SCR} = q_o - q_s(T=T_{SCR}) + q_s(T=T_{SCR}) - q_{SCR}$$
$$\simeq \Delta'(T_o - T_{SCR}) + \delta q \qquad (4.9)$$

where Δ' = rate of change of saturation specific humidity with temperature

δq = specific humidity deficit at screen height

Thus

$$E = \rho(\Delta'(T_o - T_{SCR}) + \delta q)/(r_s + r_{aE}) \qquad (4.10)$$

Now,

$$r_{aE} \simeq r_{aH} = r_a$$

Then, from Equations (4.6) and (4.7)

$$\lambda E = R_{NE} - G - (T_o - T_{SCR})(\rho c_p/r_a + b') \qquad (4.11)$$

Eliminating $T_o - T_{SCR}$ between (4.10) and (4.11)

$$E(1 + r_s/r_a) = \rho \delta q/r_a + \frac{\Delta'((R_{NE}-G) - \lambda E)}{c_p(1 + b'r_a/\rho c_p)}$$

or,

$$E(c_p(1+r_s/r_a)(1+b'r_a/\rho c_p) + \Delta'\lambda) = \rho c_p \delta q(1+b'r_a/\rho c_p)/r_a + \Delta'(R_{NE}-G)$$

Thus,

$$\lambda E = \frac{\Delta'(R_{NE}-G) + \rho c_p \delta q(1+b'r_a/\rho c_p)/r_a}{\Delta' + c_p(1+r_s/r_a)(1+b'r_a/\rho c_p)/\lambda} \qquad (4.12)$$

Writing this equation in terms of vapour pressure rather than specific humidity leads to

$$\lambda E = \frac{\Delta (R_{NE} - G) + \rho c_p (e_s - e)(1 + b' r_a / \rho c_p)/r_a}{\Delta + \gamma (1 + r_s/r_a)(1 + b' r_a / \rho c_p)} \qquad (4.13)$$

: this is the combination equation used in MORECS

4.2.2.1 Available energy: short and long-wave radiation, the effects of cloud, soil heat flux

The downward daily total of short-wave radiation at the surface (R_c) is expressed in terms of the radiation flux density (R_A) at the top of the atmosphere using the scheme of Cowley (1978) which involves application of the empirical relation.

$$R_c = R_A (\eta (a + bn/N) + c(1 - \eta)) \qquad (W\ hr\ m^{-2}) \qquad (4.14)$$

where

$$R_A = \int_{t_1}^{t_2} S \sin\Theta \, dt$$

$$= \int_{t_1}^{t_2} S \left(\sin\delta \sin\phi - \cos\delta \cos\phi \cos\frac{\pi t}{12} \right) dt$$

$$= S\left((t_2 - t_1) \sin\delta \sin\phi + \frac{12}{\pi} \cos\delta \cos\phi \left(\sin\frac{\pi t_1}{12} - \sin\frac{\pi t_2}{12} \right) \right) \qquad (4.15)$$

Θ = solar elevation

δ = solar declination

$= 0.41 \cos(2\pi(d - 172)/365)$

d = day of year (1 ≡ 1 January)

ϕ = latitude

S = solar constant

$= 1360(1 + 0.035 \cos(2\pi d/365))$ (Wm^{-2}) (4.16)

(Hughes et al 1977)

t_1 = local time of sunrise

$$= \frac{12}{\pi} \arccos(\tan\delta \tan\phi + 0.0145/(\cos\delta\cos\phi)) \quad (4.17)$$

: this expression allows for the refraction (~ 34') and sun radius (~ 16') so that sunrise occurs when the sun centre is still 50' below the horizon

t_2 = local time of sunset
$= 24 - t_1$
N = day length
$= t_2 - t_1$
$= 24 - 2t_1$
n = measured number of hours of bright sunshine
$\eta = 0$ if $n = 0$
$\eta = 1$ if $n > 0$

a and c are independent of season, with respective values of 0.24 and 0.15, varying geographically by about $\pm$ 0.02. b varies both seasonally and geographically, increasing from about 0.50 in winter to 0.55 in summer, with a further geographic variation of around 0.05.

The net shortwave radiation at the surface is

$$R_{NS} = (1-\alpha) R_c \quad (4.18)$$

where α is the albedo of the surface. Values of albedo used in MORECS for different surfaces are shown in Table 4.2.1.

Table 4.2.1 MORECS albedos

Surface type	Albedo	Surface type	Albedo
Grass	0.25	Upland	0.25
Cereals (Wheat, barley)	0.25	Riparian	0.25
Potatoes (early and maincrop)	0.25	Bare rock	0.12
		Conifers	0.12
Sugar beet	0.25	Impervious urban	0.10
Orchards	0.25	Water	0.05
Deciduous trees	0.17	Bare soil (dry)	0.10, 0.20, 0.30[a]
		Bare soil (wet)	0.05, 0.10, 0.15[a]

(a) Values refer respectively to soils of high, medium and low available water capacity

---

The values in the Table for the various types of vegetation refer to a fully developed crop cover. In the case of an incomplete cover a simple empirical correction to albedo is used:

$$\alpha = \alpha_s + 0.25\,(\alpha_c - \alpha_s)\,\mathfrak{L} \qquad \mathfrak{L} \leq 4)$$
$$= \alpha_c \qquad \mathfrak{L} > 4) \qquad (4.19)$$

where α_s = albedo for bare soil

α_c = albedo for full crop cover

$\mathfrak{L}$ = leaf area index

The incoming long-wave radiation ($R_{L\downarrow}$) is estimated using the technique of Brutsaert (1975). Unlike most other methods, Brutsaert's has a minimum of empiricism, being based on the equations of radiative transfer. The expression he derived for clear skies is

$$R_{L\downarrow} = a' \sigma K_{SCR}^4 \,(e_{SCR}/K_{SCR})^{1/7} \qquad (Wm^{-2}) \qquad (4.20)$$

where e_{SCR} = vapour pressure at screen height

K_{SCR} = screen temperature in deg K

The value of a' is slightly dependent on assumptions about the variations of temperature and vapour pressure with height in the lowest few kilometres of the atmosphere. Brutsaert's treatment suggested a value of about 1.24 but a comparison with experimental data gives a value of around 1.28 which is used in MORECS (Barrie 1981).

Upward long-wave radiation from the surface is (putting $K_{SCR} \simeq K_{SURFACE}$)

$$R_{L\uparrow} = \epsilon \sigma K_{SCR}^4 \qquad (Wm^{-2}) \qquad (4.21)$$

where the emissivity ϵ is assumed to be 0.95. The net long-wave radiation for clear skies is then

$$R_{LN} = \epsilon \sigma K_{SCR}^4 \,(1.28\,(e_{SCR}/K_{SCR})^{1/7} - 1) \qquad (Wm^{-2}) \qquad (4.22)$$

The effects of cloud on R_{LN} are assumed to be those suggested by Linacre (1968) so that the general expression is

$$R_{LN} = \epsilon\sigma K_{scr}^{4} \left(1.28 \left(e_{scr}/K_{scr}\right)^{1/7} - 1\right)\left(0.2 + 0.8 n'/N\right) \quad (Wm^{-2}) \qquad (4.23)$$

For daytime calculations n' takes a value equal to the number of hours of bright sunshine. At night the amount of cloud is smaller usually than during the day (Barrie 1980), by about 10% typically, so that $n' \simeq 1.1\, n$ (with a maximum value limited to 1.0).

Following Monteith (1958) the daytime flux density of heat into bare soil is assumed to be

$$G_d = 0.3\, R_{Nd} \qquad (4.24)$$

where R_{Nd} is the average daytime net all-wave radiation flux density, given by

$$R_{Nd} = R_{NL} + (1-\alpha)\, R_c/(t_2 - t_1) \qquad (4.25)$$

: the corresponding value for a grass-covered surface is

$$G_d = 0.2\, R_{Nd} \qquad (4.26)$$

and for other crops is

$$G_d = (0.3 - 0.03 f)\, R_{Nd} \qquad (4.27)$$

The night-time value for G is calculated using a scheme suggested by Wales-Smith and Arnott (1980). They used measurements of soil temperature at Kew with estimated soil thermal capacities to calculate the average monthly heat storage in the soil, and the corresponding average flux density of heat at the soil surface. Values of daily heat storage calculated in this way are given in Table 4.2.2:

Table 4.2.2 Average daily heat storage in soil (P) (W hr m^{-2})

J	F	M	A	M	J	J	A	S	O	N	D
-137	-75	30	167	236	252	213	69	-85	-206	-256	-206

they are assumed to apply over the whole MORECS grid. Thus the average night-time value of G (Wm^{-2}) is

$$G_n = \frac{(t_2 - t_1)\, G_d - P}{2t_1} \qquad (4.28)$$

Finally, the available energy is calculated from

$$\left.\begin{array}{l}\text{daytime available energy} = R_{Nd} - G_d \\ \text{night-time available energy} = R_{LNn} - G_n\end{array}\right\} \quad (4.29)$$

4.2.2.2 Aerodynamic resistance

The aerodynamic resistances for heat and water vapour transfer are defined by eq (4.7) and (4.8). Experimental evidence shows that they are negligibly different in magnitude. The resistances may also be defined in terms of the vertical eddy diffusion coefficient for heat and water vapour transfer ($K_{H,E}(z)$), thus demonstrating the role of atmospheric turbulence in transferring heat and water vapour away from the surface. In this form the definition is

$$r_{aH} = r_{aV} = r_a = \int_{z_{T,q}}^{z-d} (1/K_{H,E}(z))\, dz \quad (4.30)$$

Here $z_{T,q}$ is the roughness length of the surface for heat and water vapour transfer. Momentum may be transferred to surfaces by pressure forces as well as molecular diffusion and so the roughness length for momentum transfer (z_o) is larger than $z_{T,q}$. Thom (1975) developed this idea and showed that

$$z_{T,q} \simeq 0.2\, z_o \quad (4.31)$$

Typical values for z_o are about $0.1h$, where h is the crop height, and so $z_{T,q} \simeq 0.02h$.

In equation (4.30) the upper limit of integration is $z-d$, rather than z . This acknowledges that the effective mean height at which the heat and water vapour originates is $d+z_{T,q}$, where d is the zero-plane displacement height: it has a typical value of about $0.6h$ (Monteith 1973). The temperatures and humidities which MORECS uses are measured over short grass at a height of 1.2 m (screen height), for which d can be ignored. The assumption is made that these data will also apply at a height of 1.2 m above the zero-plane of any other surface. Hence the MORECS r_a should be defined by

$$r_a = \int_{z_{T,q}}^{z'-d} (1/K_{H,E}(z))dz \quad (4.32)$$

where

$$z' = 1.2 + d \qquad \text{(metres)}$$

In conditions of near-neutral atmospheric stability the variations of wind and temperature with height are logarithmic, and equation (4.32) may be integrated to give (Thom and Oliver 1977).

$$r_a = (1/k^2\, U(z'))\, \ln(1.2/z_o)\, \ln(1.2/z_{T,q}) \qquad (4.33)$$

MORECS assumes that its measured 10 m winds ($U_m(10)$) are equal to the wind speed $U(10+d)$ at $10+d$ metres above the surface underlying the crop, or that wind speeds at 10 m above the zero-plane are the same for different crops. This is a bad approximation over very tall, very rough crop covers (eg conifers) and for these cases, following Oliver (1974), the relation

$$U(10+d) = 0.6\, U_m(10) \qquad (4.34)$$

is used, in a somewhat different treatment outlined at the end of this section. From the logarithmic wind profile it may be shown that

$$U(z')/U(10+d) = \ln(1.2/z_o)/\ln(10/z_o) \qquad (4.35)$$

Using the relation $z_o = 0.1h$, and equations (4.33), (4.35), and where appropriate (4.34), one may then calculate r_a , noting that eq (4.33) and (4.35) give

$$r_a = (6.25/U(10+d))\, \ln(10/z_o)\, \ln(6/z_o) \qquad (4.36)$$

The treatments described by the foregoing equations are poor approximations over very rough surfaces where the level ($1.2+d$) metres may be well within, rather than above, the foliage. In these cases the upper reference level is taken to be ($10+d$) metres above the ground surface, and the vapour pressure deficit calculated from the screen data is assumed to apply at this height over the forested area. r_a is then given by

$$r_a = (6.25/U(10+d)) \ln(10/z_o) \ln(50/z_o) \qquad (4.37)$$

Then, for mature conifers and deciduous trees (in full leaf), for which $z_o \simeq 1$ m,

$$r_a = 56.3 / U(10+d)$$

$$\simeq 94 / U_m(10) \qquad (4.38)$$

Use of the neutral forms for r_a (eq (4.36), (4.38)) requires some justification. Thompson (1981) made exact calculations of evapotranspiration using the Penman-Monteith equation with given input values for available energy, vapour pressure deficit, wind speed, surface roughness, temperature and surface resistance, with full allowance for non-neutral stability in calculating r_a, and with and without correction to available energy resulting from surface heating: the results were compared with estimates made using the method outlined above, and with estimates obtained using the modified form of Penman's original form for r_a suggested by Thom and Oliver, also with and without allowance for the effects of surface heating on available energy. The method described in detail above gave the best agreement with the exact calculations, and for typical values of the input variables was usually within better than 10% of the exact model. It showed a small overall bias towards underestimation, but this conveniently compensates to some extent for neglect of the available energy used in photosynthesis by the transpiring crop.

The crop heights used by MORECS are shown in Table 4.2.3. Values for annual crops are assumed to vary during the season according to the relation

$$\begin{aligned} h &= h_1 + (h_2 - h_1)(d - d_e)/(d_f - d_e) && d_e < d < d_f \\ &= h_2 && d_f < d < d_h \end{aligned} \qquad (4.39)$$

where h_1, h_2 are the minimum and maximum heights listed in Table 4.2.3

d = day of year

d_e = (spring-sown crops) assumed emergence date) Annexe A

= (autumn-sown crops) assumed date of start of spring growth after winter dormancy - Annexe A

d_f = assumed date when crop reaches maximum height

d_h = assumed harvest date

Deciduous trees, including orchard trees, are assumed to foliate, and defoliate, over periods of 40 days, with linear changes of their effective heights over these periods.

Table 4.2.3 Effective crop heights used in MORECS

Crop	Height (m)	Crop	Height (m)
Grass	0.15	Orchards[c]	0.15, 2.0, 3.0
Spring barley[a]	0.05 - 0.8	Conifers	10.0
Winter wheat[b]	0.08 - 0.8	Upland	0.15
Winter barley[b]	0.08 - 0.8	Impervious urban	10.0
Potatoes[a]	0.05 - 0.6	Bare rock	0.05
Sugar beet[a]	0.05 - 0.35	Water	0.005
Deciduous trees[c]	0.15, 2.0, 10.0	Bare soil	0.05

(a) Range of values for spring-sown crops refer to the period emergence to harvest

(b) Range of values for autumn-sown crops refer to the over-winter period, up to harvest

(c) First value is for defoliated trees, the second at leaf emergence, and the third for full leaf

4.2.2.3 Surface resistance when soil moisture is not limiting

Correct specification of surface resistance r_s is crucial to the satisfactory running of MORECS. r_s varies widely with type and age of crop, and with external factors such as soil moisture deficit. It is not possible to include these variations in other than a simple fashion in MORECS, partly to keep the complexity of the computation scheme within bounds, but also because data on many of the physiological responses are at present inadequate. The aim has to be to incorporate a realistic scheme which will account for seasonal changes including variable leaf area index for the main surface types which are considered. For most of these surfaces it is necessary to calculate r_s on a daily basis for both day and night-time, using where appropriate data given in Annexe A.

For seasonal crops the surface will range from bare soil, to moderately or densely foliated. Water may be extracted directly from both the soil and the crop, and the surface resistance has to be calculated taking both these processes into account. The basic scheme follows that suggested by Grant (1975) and uses the expression

$$1/r_s = (1-A)/r_{sc} + A/r_{ss} \qquad (4.40)$$

where r_{sc} = surface resistance of the crop, freely supplied with water, and dense enough for evaporation from the soil to make a negligible contribution

r_{ss} = surface resistance of bare soil (assumed to be 100 sm^{-1} for wet soil)

$A = f^{LAI}$

Grant found that f for barley was about 0.7, and this value is assumed to apply to all the crops treated by MORECS. Eq (4.40) was derived for daytime conditions and assumes that the parallel contributions of soil and crop resistance to their combined resistance are roughly proportional to the amount of incident radiation which each of them absorbs. At night the leaf stomata are closed and the crop resistance r_{sc} is assumed to be the sum of the individual leaf (cuticular) resistances in parallel. These in turn are taken to be directly in parallel with the soil resistance so that

$$1/r_s = 2\xi/r_{sc}(night) + 1/r_{ss} \qquad (4.41)$$

A typical leaf resistance when stomata are closed is several thousand sm^{-1}: the form of eq (4.41) used by MORECS is

$$1/r_s = \xi/2500 + 1/r_{ss} \qquad (4.42)$$

It is not possible to justify this last equation convincingly since it ignores the effects of turbulent resistances in the crop canopy. However, evaporation is usually small at night so errors introduced by eq (4.42) will also be small.

Values for r_{sc} which are used by MORECS during the daytime are given in Table 4.2.4. Corresponding values of maximum leaf area index are given in Table 4.2.5.

Leaf areas of the cereals are assumed to increase linearly according to the relation

$$\xi = (\xi_{max} - 0.1)(d - d_e)/(d_f - d_e) + 0.1 \qquad d_e < d < d_f \qquad (4.43)$$

Leaf areas remain unchanged between full development and harvesting, but the effects of senescence are included by writing

$$r_{sc} = r_{sc}(min) + 50\left(\frac{d-d_f}{d_h-d_f}\right) + 500\left(\frac{d-d_f}{d_h-d_f}\right)^3 \qquad (4.44)$$

so that r_{sc} is large ($\simeq$ 600 sm^{-1}) at harvest.

Leaf area development for the rootcrops is also represented by eq (4.43), with a constant value after $d = d_f$, but r_{sc} is set to a constant value throughout the season.

Equation (4.43) is also used for deciduous trees during foliation. r_s follows from application of eq (4.40).

Table 4.2.4 Daytime values of surface resistance for dense green crops freely supplied with water

Type of crop	(sm^{-1})
Grass, riparian land	80 (Jan), 80, 60, 50, 40, 60 (June) 60, 70, 70, 70, 80, 80 (Dec)
Cereals	40
Potatoes, sugar beet	40
Deciduous trees	80
Conifers	70[a]
Upland[b]	120 (Jan–Mar, Oct–Dec): 100 (Apr–Sept)
Orchards	See text
(Bare soil	100)
(Water	0)

(a) at zero vapour pressure deficit and 20 deg C: assumed independent of r_{ss}, ie $r_s = r_{sc}$

(b) assumed independent of leaf area of ground cover, ie $r_s = r_{sc}$

Table 4.2.5 Maximum leaf area indexes

Crop	Green leaf area index
Grass, riparian land	2.0 (Jan), 2.0, 3.0, 4.0, 5.0, 5.0 (June) 5.0, 5.0, 4.0, 3.0, 2.5, 2.0 (Dec)
Cereals	5.0
Potatoes	4.0
Sugar beet	4.0
Deciduous trees	6.0
Conifers	6.0[a]
Orchards	See text

(a) constant throughout year

A temperature dependence for r_{sc} in the case of conifers is represented by

$$\left.\begin{array}{lll} r_{sc} = 25\, r_{sc}(min)/(T_{scR}+5) & -5<T_{scR}<20 \\ = r_{sc}(min) & T_{scR}>20 \\ = 10^4 & T_{scR}<-5 \end{array}\right\} \quad (4.45)$$

The well-documented response to vapour pressure deficit (eg Grace et al 1975) is accounted for by writing

$$\left.\begin{array}{lll} r_{sc} = r_{sc}(\delta e=0)/(1-0.05\,\delta e) & \\ & \delta e < 20\,mb \\ = 10^4 & \delta e > 20\,mb \end{array}\right\} \quad (4.46)$$

r_s is then calculated using eq (4.40).

Orchards are assumed to be largely grass-covered, so that the values of r_s calculated for grassland are used when the trees are not in leaf. A grass cover with a leaf area index of 2.5 is maintained while the tree leaves develop, and also during the period of tree leaf maturity when the leaf area index of the trees is set to 2.5. Thus the calculation of r_s outside the leafless season has to consider resistances of soil, grass and tree. This is done first by calculating the combined resistance of tree and grass (r_s (tree/grass)) using the relation

$$1/r_s(tree/grass) = (0.7)^{\ell_t}/r_{sc} + (1-(0.7)^{\ell_t})/r_{st} \quad (4.47)$$

where

$$\left.\begin{array}{lll} \ell_t = \text{tree leaf area index} & \\ = 2.5(d-d_e)/(d_f-d_e) & d_e<d<d_f \\ = 2.5 & d_f<d<d_h-40 \\ = 2.5\,(d_h-d)/40 & d_h-40<d<d_h \end{array}\right\} \quad (4.48)$$

r_{st} = surface resistance of a dense structure of trees (assumed to be 80 sm^{-1})

r_{sc} = surface resistance of a dense grass cover (assumed to be 50 sm^{-1} during the period when the trees are in leaf)

This resistance is combined with soil surface resistance using the relation

$$1/r_s = (0.7)^{\ell_{tg}}/r_{ss} + (1-(0.7)^{\ell_{tg}})/r_s(tree/grass) \quad (4.49)$$

where $r_{ss} = 100\ sm^{-1}$

$\sum L_{tg}$ = sum of grass and tree leaf area indices

: eq (4.47) and (4.49) reduce to the usual relation for a grass-covered surface (eq (4.40)) when $\sum L_t = 0$.

Night-time values of r_s for permanent crops (conifers, grass, riparian land, upland) are calculated using eq (4.42). Orchard values of r_s at night use the same equation, but with leaf area set equal to the sum of grass and tree leaf areas.

4.3 Calculation of actual evaporation using a soil-moisture extraction model

4.3.1 Introduction

Numerous experimental studies have shown that evaporation (AE) falls increasingly below the potential rate (PE) as the amount of water available in the soil decreases. The point at which AE begins to depart significantly from PE depends to some extent on the magnitude of the evaporative demand, and the hydraulic properties of the moist soil. The oft-quoted experiment of Denmead and Shaw (1962) showed that AE remained close to PE until most of the available water was exhausted, when the evaporative demand was very low, but that at very high values of demand the AE fell to small values even when considerable amounts of soil moisture remained. These results are consistent with water flowing from moister areas to the root zones of plants at a sufficient rate to maintain plant turgour and hence open stomata only when hydraulic conductivity is large enough to prevent excessive drying out around the roots.

Different soils have not only different volumes of water available to plants, but also different hydraulic conductivities. Sands (low available water capacity) for example are able to sustain relatively high rates of evaporation until much of the available water is exhausted, whereas clays (medium to high available water) with their lower conductivities are associated with AE falling well below PE long before all available water has gone. MORECS performs its calculations for soils of low, medium and high available water content, and for completeness, should perhaps give outputs in each case for low, average and high hydraulic conductivity. This would lead to 9 different sets of outputs, which is an unrealistically large number for this type of operational model. Results are calculated for only "average" hydraulic conductivities there-

fore. The effects noted by Denmead and Shaw are ignored, for two reasons. First, when the evaporative demand is small, for example on humid, cloudy days in summer, or in winter, the soil is usually well supplied with water so that AE $\simeq$ PE regardless of the magnitude of hydraulic conductivity. Second, during the main seasons of evaporation the evaporative demand usually only rises much above the daily average when the soil is very dry; in this last case the evaporative demand may become very large, but AE/PE will then be small due to low available water and the variations of this ratio with hydraulic conductivity will then be of little consequence. If MORECS had been developed for use in climates where very large fluctuations of evaporative demand occur during a season even when considerable amounts of available water remain, then it would have been appropriate to attempt to model the effects noted by Denmead and Shaw for at least average hydraulic conductivities.

4.3.2 Relationship between surface resistance and soil moisture deficit

The basis of MORECS' soil moisture extraction model is the assumption that, for a dense crop intercepting the incident radiation completely, the surface resistance remains constant while the first 40% of the available water is extracted but then increases progressively, to very large values when all available water is exhausted. This is broadly consistent with experimental results for crops subjected to a moderate evaporative demand (eg Russell 1980). A similar assumption is made for evaporation of water from bare soil, again in moderate agreement with experiment (Saxton et al 1974), although the quantities of water which may be extracted are smaller here.

Typical crops do not intercept all incident radiation, especially during early growth, and so the contribution to evaporation from the underlying soil must also be considered. This is done by relating r_{ss} to the soil moisture deficit and then combining it with a correspondingly corrected r_{sc}, using the relations discussed in § 4.2.2.3.

MORECS uses the simplifying assumption that the available water is held in two reservoirs X and Y which at any time may contain reserves of x and y mm. All water in X is freely available, while that in Y becomes increasingly difficult to extract as y decreases. Thus the

total (maximum) available water ($x_{max} + y_{max}$) is distributed 40% in X and 60% in Y. Water is drawn from the soil until X is completely exhausted, when extraction from Y begins. Rainfall is assumed to recharge X first of all, and only replenish Y when X is filled. (X and Y are sometimes thought of as two discrete soil layers, with X adjacent to the surface and overlying Y, but there is no reason why these should be so, and these concepts are deliberately avoided here).

Two distinct cases have to be considered. In the first it is assumed that X contains x mm of water (the quantity in Y is irrelevant here). The values for r_{sc} discussed earlier for potential evaporation will therefore apply because x is greater than zero. However the value of 100 sm^{-1} is only assigned to r_{ss} provided x_{max} is greater than $x(\text{bare soil})_{max}$: otherwise a rough and arbitrary correction is made by writing

$$r_{ss} = 100 x_{max} / (x + 0.01 x_{max}) \quad sm^{-1} \qquad (4.50)$$

r_s then follows from application of the appropriate equation (usually (4.40). In the second case the water in the top **layer** is exhausted so that $r_{ss} = 10^4$ sm^{-1}, and r_{sc} is increased according to the size of y. The relation used here is derived from data presented by Russell (1980) and is

$$r_{sc}(y) = r_{sc}\left(3.5\left(1 - y/y_{max}\right) + \exp\left(0.2\left(y_{max}/y - 1\right)\right)\right) \qquad (4.51)$$

When the surface is bare soil (without a crop) the surface resistance is calculated from

$$\left.\begin{aligned} r_s = r_{ss} &= 100\ sm^{-1} \quad \left(x(\text{bare soil})_{max} > x > 0\right) \\ &= 100\left(3.5\left(1 - y/y(\text{bare soil})_{max}\right)\right. \\ &\quad \left. + \exp\left(0.2\left(y(\text{bare soil})_{max}/y - 1\right)\right)\right) \\ &\quad (x = 0) \end{aligned}\right\} \qquad (4.52)$$

4.3.3 Available soil moisture for different crops

Values of available water capacity selected for MORECS are summarized in Table 4.3.1. Those listed are for soils of medium

Table 4.3.1 MORECS values of available water capacity

Surface cover	Available water (mm)
Grass	125
Cereals	140(a)
Potatoes	90(a)
Sugar beet	140(a)
Deciduous trees	175(b)
Conifers	175
Upland	50
Orchards	150
Bare soil	20

(a) at maximum rooting depth

(b) at full foliation

capacity: values 25% larger and smaller are used to arbitrarily define soils of high and low capacity. In the case of spring barley and root crops the available water increases from approximately twice that for bare soil at the time of emergence of the crops, linearly to the maximum values given in the Table which are assumed to be achieved when maximum cover is reached ($d = d_f$). After harvest or leaf fall the surface is assumed to return to bare soil. Winter cereals are treated similarly, except that after harvest a bare soil is assumed until the end of December, and thereafter a sparse crop ($f = 0.5$, $h = 0.08$ m, available water = 3.75 x available water for bare soil) up to the assumed date of start of spring growth. No account is taken of deep rooting by trees which may allow some extraction from potentially much larger reserves in drought conditions.

4.4 Calculation of water balance and excess rainfall

4.4.1 Treatment of intercepted water, including condensation

When the MORECS estimate of night-time evaporation is negative, r_s is set equal to zero and the calculation performed again in order to provide an estimate of condensation. The treatment of interception is simplified by assuming that the effective daily rainfall is the sum of this condensation and rainfall.

A proportion (p) of the effective rainfall is intercepted by the crop overlying the soil, with a dense crop intercepting at a higher rate than a **sparse one.** The relation used is

$$p = 1 - (0.5)^{\xi} \qquad (p \leq p_{max}) \qquad (4.53)$$

Substantial falls of rain will completely wet the canopy and so p is constrained not to exceed that value p_{max} which produces full wetting. This interception capacity is $q\xi$ where q is the capacity per unit leaf area index, assumed to be 0.2 mm. Thus,

$$I = Rp \leq 0.2\xi \qquad (4.54)$$

where I is the interception and R the rainfall. In practice there may be more than one rainfall event each day, or some evaporation of intercepted water may occur while rain is still falling. In MORECS it is assumed that evaporation of intercepted water is slow in winter months when the maximum daily interception I_D is given by eq (4.53) and (4.54). In summer it is assumed that because of the effect just mentioned, the daily loss will be typically twice the value calculated from (4.53), within the limits $I_D \leq 2I \ast R$. Factors used to multiply I for each month are given in Table 4.4.1.

Table 4.4.1 Factor enhancing simple interception to allow for multiple daily rainfall events, or for evaporation of intercepted water while rain is falling

Month	J	F	M	A	M	J	J	A	S	O	N	D
Factor	1.0	1.0	1.2	1.4	1.6	2.0	2.0	2.0	1.8	1.4	1.2	1.0

Each daytime or night-time calculation is performed with $r_{sc} = 0$ while intercepted water remains. Once the foliage is dry the rate of water loss from the surface is calculated for the remainder of the period using the r_{sc} value for dry foliage. Thus, total water loss from the surface is the sum: intercepted water + (rate of water loss (dry foliage)) x number of hours while foliage is dry. On those occasions when the evaporative demand is insufficient to evaporate all the intercepted water the amount remaining at the end of the day is not carried over but is assumed to fall to the soil.

4.4.2 Soil moisture deficit and excess rainfall

The information given in previous sections explains how the daily evaporation is calculated. The difference between this evaporation and rainfall, when added to the previous day's soil moisture deficit, yields the current soil moisture deficit. Some clarification of this procedure is required for seasonal crops after harvest, before emergence of the new crop. In this period there will be reserves x mm in reservoir X_{crop} and y mm in Y_{crop}. Until the newly-sown crop emerges it is assumed that there is no root system which can extract moisture from Y_{crop}: over this period then the only change to y will be increases due to any rainfall remaining after X_{crop} is filled. Also the absence of a root system usually means that X_{crop} will not be fully available for evaporation. Thus the maximum amount of available water after harvest, all assumed residing in a part of X_{crop}, is the fraction

$$(x_{(bare\ soil)_{max}} + y_{(bare\ soil)_{max}}) . x/x_{max}$$

: the remainder of the water in X_{crop} is not available, and can only be changed by residual rainfall which remains after the other part of X_{crop} (that available for bare soil evaporation) is replenished. Thus the fraction of the X_{crop} water, calculated as above at harvest, is assumed transferred to two reservoirs $X_{(bare\ soil)}$ and $Y_{(bare\ soil)}$ in the proportions 60% : 40%.

Rainfall is assumed to fill first X, then Y, at a very rapid rate (in the case of bare soil after the harvest, rain will fill X, $Y_{(bare\ soil)}$, then the remaining part of X_{crop} and finally

Y_{crop} . The excess rain after these reservoirs are replenished (at which point the soil will be at field capacity) is assumed to be "hydrologically effective rainfall".

No attempt is made to model or estimate run-off.

4.4.3 Calculation of real land use values of PE, AE, SMD and HER

Real land use values of PE, AE, SMD and HER are calculated for each square using estimates of percentage of various surfaces in each square (Annexe B). The estimates were obtained from a variety of sources. The 14 real land use types are correlated with the 12 surfaces types used in MORECS according to Table 4.4.2.

Table 4.4.2 Relation between real land use and MORECS surface types

Real land use	Representation in MORECS outputs
1. Impervious urban	Impervious urban (page 57)
2. Open water	Open water
3. Riparian	Riparian
4. Bare Rock	Bare rock (page 57)
5. Conifers	Conifers
6. Heather, gorse	Upland
7. Permanent grass	Grass
8. Deciduous trees	Deciduous trees
9. Orchards	Orchards
10. Rough grazing	Upland
11. Cereals	((Winter wheat + winter barley)/2 + spring barley)/2
12. Potatoes	(Main crop + earlies)/2
13. Temporary grass	Grass
14. Fallow	Bare soil

Real land use estimates of PE, AE, SMD and HER for each square are obtained from the MORECS outputs weighted according to Table 4.4.1 and the percentages given in Annexe B, and then summed.

4.5 MORECS outputs

MORECS users have widely different applications for its outputs so a number of output options are provided. This number has to be limited, for operational reasons, but the information provided caters for most of the needs which have been expressed.

At present there are five options available, which provide data in both tabular and graphical (map) form.

(i) Weekly issues of 13 maps showing, for soils of medium available water capacity, grid square values of PE, AE, SMD and HER for grassland and real land use, and square values of the 5 basic meteorological variables (sunshine, temperature, vapour pressure, wind speed and rainfall): a written commentary is included fortnightly and summary maps monthly (total PE, AE and HER for the month, end of month SMD for grass, average daily temperature, vapour pressure and wind, total sunshine and rainfall)

(ii) As (i), but without the maps referring to real land use

(iii) Fortnightly issues of 3 maps showing PE for grass, and SMD for grass and real land use, together with the written commentary

(iv) Weekly issues giving in tabular form PE, AE, SMD and HER for 3 soils and 13 crops/surface types, plus values of the meteorological variables, one square per sheet

(v) A table on 6 sheets, issued weekly, showing for soils with medium available water capacity PE, AE and SMD for six crops, and also the meteorological data, for all 190 MORECS squares.

A selection of one or more of these options satisfies the requirements of most users.

Examples of forms of output are given in Annexe C.

4.6 Comparisons between MORECS outputs and neutron probe data

Some 25 station years of neutron probe SMD data were used in the verification of the MORECS model. The field data covered several crop types and a variety of soils during the period 1970 to 1980. Results of the comparisons which are presented here refer to at least one set of

neutron probe data for each of the years for which probe data are available (Table 4.6.1).

Table 4.6.1 Neutron probe data

	Year	Place	Crop	Soil AWC
1.	1970	Sutton Bonington	Spring barley	Low
2.	1972	Sutton Bonington	Spring barley	Low
3.	1975	Sutton Bonington	Winter wheat	Medium
4.	1976	Sutton Bonington	Winter wheat	Medium
5.	1976	Broom's Barn	Sugar beet	High
6.	1977	Westbury-on-Trym	Grass	High
7.	1978	Near Finningley	Potatoes	Medium
8.	1979	Broom's Barn	Sugar beet	High
9.	1980	Hurley	Grass	High
10.	1981	Hurley	Grass	High

Probe SMD's were compared with estimates obtained using the MORECS routines (Annexe D); the input meteorological data were those from the observing station nearest each probe site. However, rainfall data from, or near, the actual probe sites were used where available (exceptions are listed in the Annexe). The standard MORECS available water capacities, sowing and harvesting dates (Annexe A) were used unless these differed markedly from the actual data, which were then used instead.

Inspection of the diagrams in Annexe D indicates the success with which MORECS performs. Some of the anomalies can be clearly attributed to the employment of rainfall figures which were not obtained at the actual probe site (eg Sutton Bonington 1972, during the first part of June). There are other anomalies, but the evidence from these 10 cases, and from others used but not presented here, supports on the whole the idea that this new version of MORECS gives generally acceptable values of SMD.

ACKNOWLEDGEMENTS

Thanks are due to E Garwood and K C Tyson (Grassland Research Institute), A Messem (Broom's Barn), D Hall (Soil Survey), and J D Pidgeon (ICI) and P Francis (Met Office) for provision of neutron probe data for MORECS verification. A Woodcock, M Field and R D'Costa have provided much assistance in implementing this new version of MORECS, and their help is also acknowledged.

REFERENCES

Barrie, I A 1980 Relationship between sunshine, cloud amount and net long wave radiation Part I: The diurnal and annual distribution of total and low cloud amounts. Agricultural Memorandum No 893 (Unpublished paper)*

Barrie, I A 1981 Relationship between sunshine, cloud amount and net long wave radiation Part II: A comparison of some formulae available to calculate net long wave radiation. Agricultural Memorandum No 923 (Unpublished paper)*

Barrie, I A and Wylie, M C 1980. Further investigation of relationships between day, night and 24-hourly averages of temperature, wind speed and vapour pressure. Agricultural Memorandum No 902 (Unpublished paper)*

Brutsaert, W 1975 On a derivable formula for long wave radiation from clear skies. Water Resources Research 11, 742-744.

Cowley, J P 1978 The distribution over Great Britain of global solar irradiation on a horizontal surface. Meteorological Magazine 107, 357-373.

Denmead, O T and Shaw R H 1962 Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agronomy J, 54, 385-390.

Grant, D 1975 Comparison of evaporation from barley with Penman estimates. Agricultural Meteorology, 15, 49-60.

Grace, J., Malcolm, D C and Bradbury, I K 1975 The effect of wind and humidity on leaf diffusion resistance in Sitka spruce seedlings. Journal Applied Ecology 12, 931-940.

Hughes, T., McMullen, J T., Morgan, R and Murray, R D 1977 On the optimum orientation of solar collectors. Energy Research, 1, 143-156.

Linacre, E T 1968 Estimating the net radiation flux. Agricultural Meteorology, 5, 49-63.

Monteith, J L 1958 The heat balance of soil beneath crops. Arid Zone Research XI, Climatology and Microclimatology, Proc Canberra Symposium, Oct 1956 (UNESCO), 123-127.

Monteith, J L 1973 Principles of Environmental Physics. Edward Arnold, London.

Monteith, J L 1981 Evaporation and surface temperature. Quart. J R Met Soc, 107, 1-27.

Oliver, H R 1974 Wind speed modification by a very rough surface. Meteorological Magazine, 103, 141-145.

Penman, H L 1948 Natural evaporation from open water, bare soil and grass. Proc R Soc A, 193, 120-145.

Russell, G 1980 Crop evaporation, surface resistance and soil water status. Agricultural Meteorology, 21, 213-226.

Saxton, K E., Johnson, H P and Shaw, R H 1974 Modelling evapotranspiration and soil moisture, Trans ASAE, 17, 673-677.

Shearman, R J and Salter P M 1975 An objective rainfall interpolation and mapping technique U G G I, Ass Int Sci Hydro , Bull Sci Hydro , 20, 353-369.

Thom, A S 1975 Momentum, Mass and Heat Exchange of Plant Communities, veg. and the Atmosphere. Vol 1 (ed. Monteith, J L) Academic Press 57-109

Thom, A S and Oliver, H R On Penman's equation for representing regional evaporation. Quart J R Met Soc, 103, 345-357.

Thompson, N 1981 A comparison of formulae for the practical calculation of evapotranspiration during the daytime. Agricultural Memorandum No 920 (Unpublished paper)*

Wales-Smith, B G., and Arnott, J A 1980 The evaporation calculation system used in the United Kingdom (Unpublished paper)*

* Available from National Meteorological Library, Bracknell.

Annexe A Dates assumed for crop development

This annexe gives the year days (eg 365 = 31 December) (Table A2) for each grid square for sowing, harvesting etc of the various crops. Intermediate stages are determined from these year days, using the information given in Table A1.

Table A1 Year days for emergence etc

Crop	day of sowing (d_s)	Start of spring growth, or emergence	day full cover is reached (d_f)	day of harvest (d_h)
Spring barley	*	$d_s + 15$	$d_h - 60$	*
Winter wheat	*	$d_h - 156$	$d_h - 60$	*
Winter barley	*	$d_h - 145$	$d_h - 60$	*
Early potatoes	*	$d_s + 25$	$d_s + 90$	*
Main crop potatoes	*	$d_s + 25$	$d_s + 90$	*
Sugar beet	*	$d_s + 64$	$d_s + 101$	*

* obtained from figures A1-A6

Orchards and deciduous trees (figures A7, A8) are treated by assuming that 40 days elapse between bud burst and full cover, and also between onset of autumn senescence and complete leaf fall.

Winter cereals are assumed to emerge on 1 January, obviously later than reality, but this makes a negligible difference to calculated PE etc in autumn and early winter, and allows a substantial simplication of the computer routines.

Take as an illustrative example spring barley growing in square 94. Then Table A1 and figure A1 give the following dates

	Year Day	Date
Sown	80	21 March
Emerged	95	5 April
Full cover	176	25 June
Harvest	236	24 August

(-1 in any square in figures A1-A8 indicates that the crop in question is grown in insignificant quantities in that square).

Table A2

DATE TO DAY OF YEAR

DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	DATE
1	1	32	60	91	121	152	182	213	244	274	305	335	1
2	2	33	61	92	122	153	183	214	245	275	306	336	2
3	3	34	62	93	123	154	184	215	246	276	307	337	3
4	4	35	63	94	124	155	185	216	247	277	308	338	4
5	5	36	64	95	125	156	186	217	248	278	309	339	5
6	6	37	65	96	126	157	187	218	249	279	310	340	6
7	7	38	66	97	127	158	188	219	250	280	311	341	7
8	8	39	67	98	128	159	189	220	251	281	312	342	8
9	9	40	68	99	129	160	190	221	252	282	313	343	9
10	10	41	69	100	130	161	191	222	253	283	314	344	10
11	11	42	70	101	131	162	192	223	254	284	315	345	11
12	12	43	71	102	132	163	193	224	255	285	316	346	12
13	13	44	72	103	133	164	194	225	256	286	317	347	13
14	14	45	73	104	134	165	195	226	257	287	318	348	14
15	15	46	74	105	135	166	196	227	258	288	319	349	15
16	16	47	75	106	136	167	197	228	259	289	320	350	16
17	17	48	76	107	137	168	198	229	260	290	321	351	17
18	18	49	77	108	138	169	199	230	261	291	322	352	18
19	19	50	78	109	139	170	200	231	262	292	323	353	19
20	20	51	79	110	140	171	201	232	263	293	324	354	20
21	21	52	80	111	141	172	202	233	264	294	325	355	21
22	22	53	81	112	142	173	203	234	265	295	326	356	22
23	23	54	82	113	143	174	204	235	266	296	327	357	23
24	24	55	83	114	144	175	205	236	267	297	328	358	24
25	25	56	84	115	145	176	206	237	268	298	329	359	25
26	26	57	85	116	146	177	207	238	269	299	330	360	26
27	27	58	86	117	147	178	208	239	270	300	331	361	27
28	28	59	87	118	148	179	209	240	271	301	332	362	28
29	29		88	119	149	180	210	241	272	302	333	363	29
30	30		89	120	150	191	211	242	273	303	334	364	30
31	31		90		151		212	243		304		365	

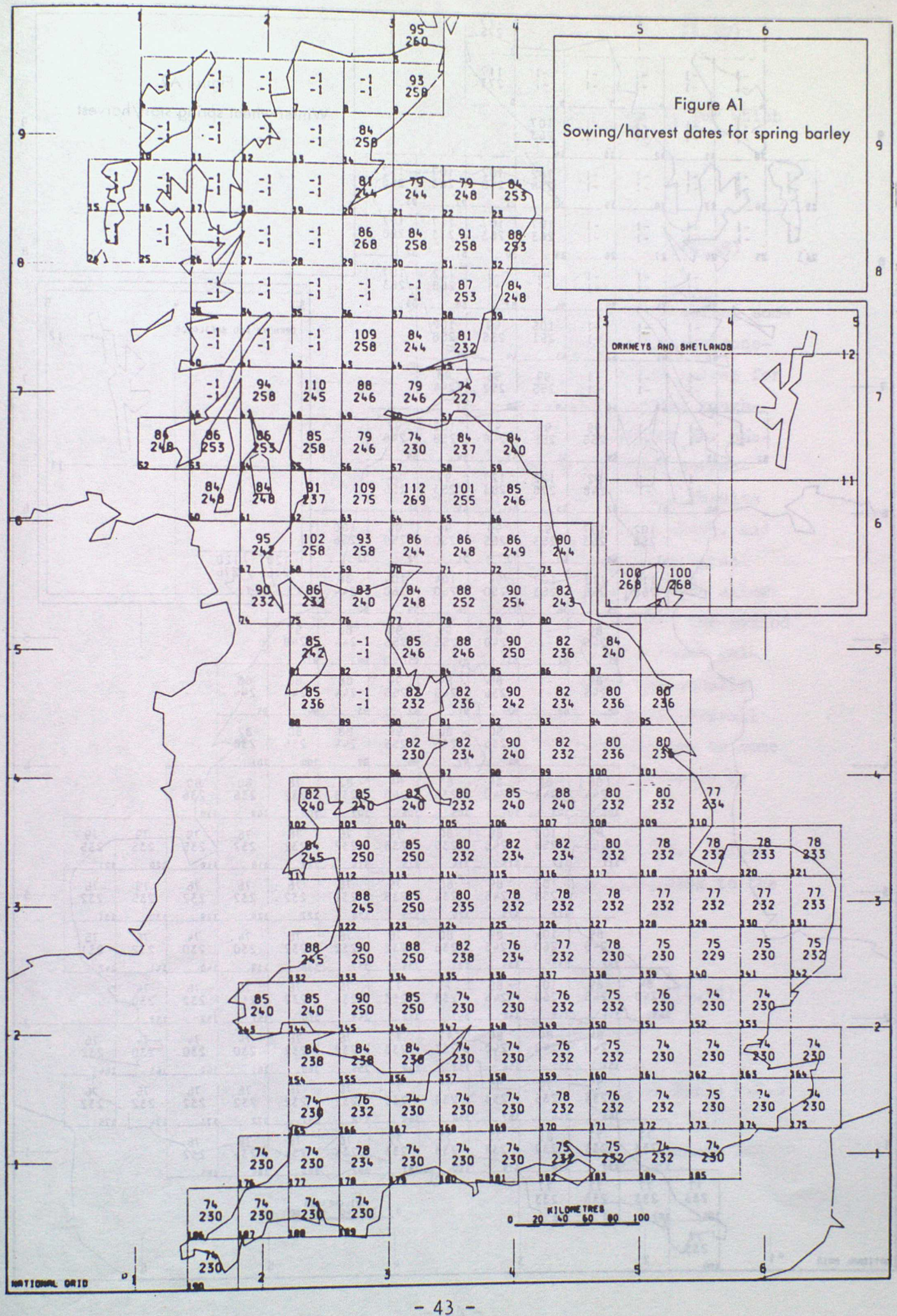


Figure A1
Sowing/harvest dates for spring barley
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

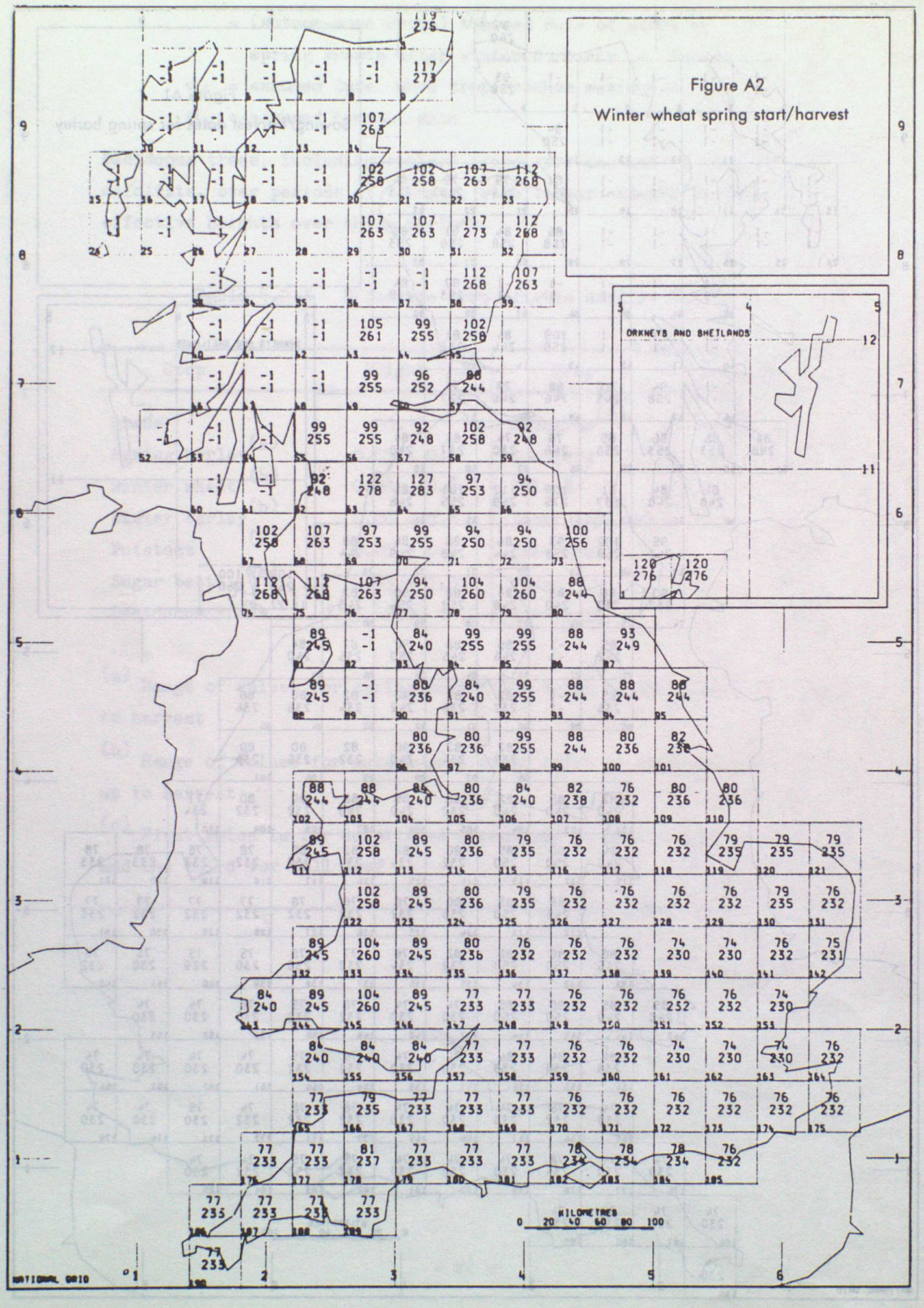


Figure A2
Winter wheat spring start/harvest
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

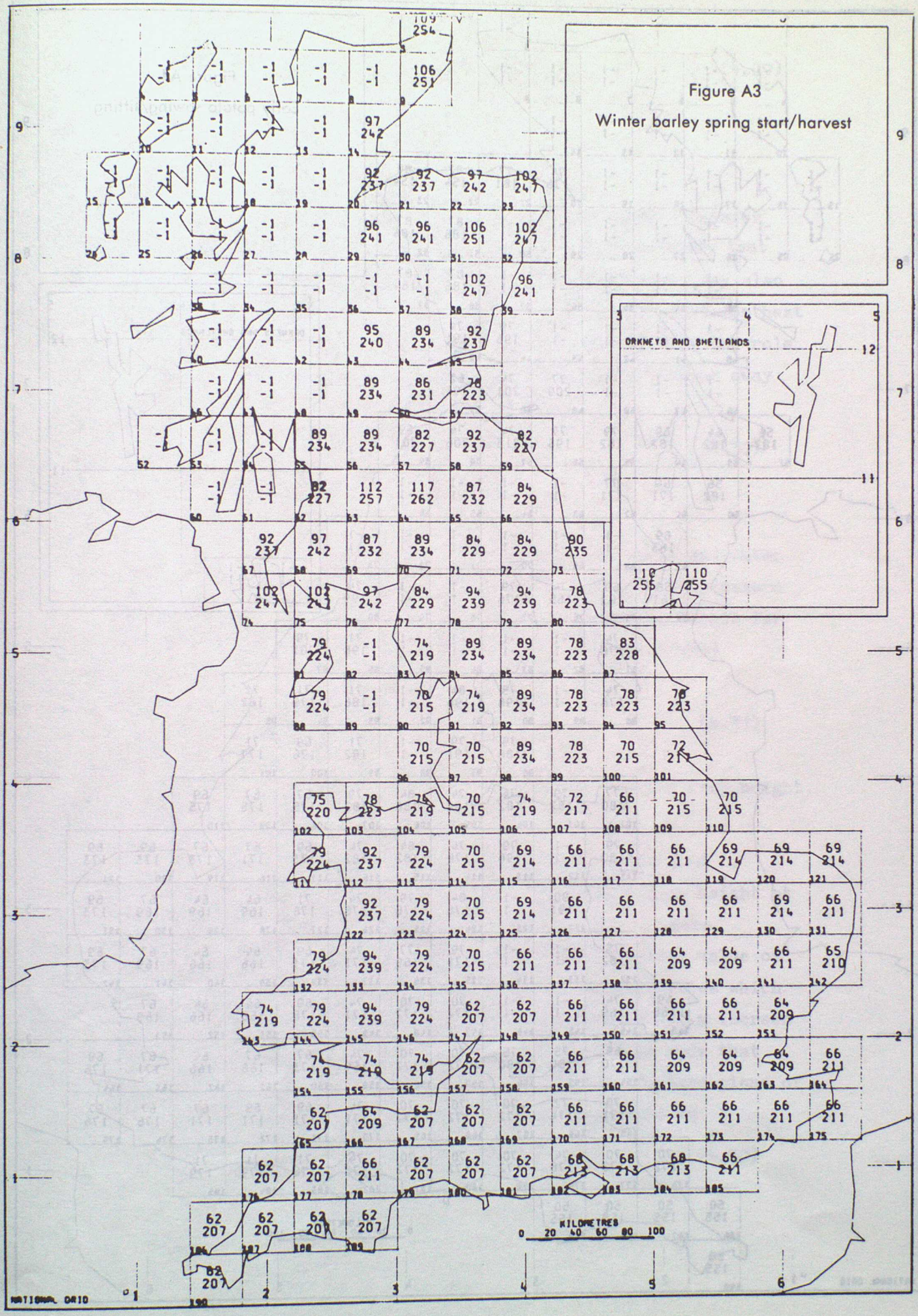


Figure A3
Winter barley spring start/harvest
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

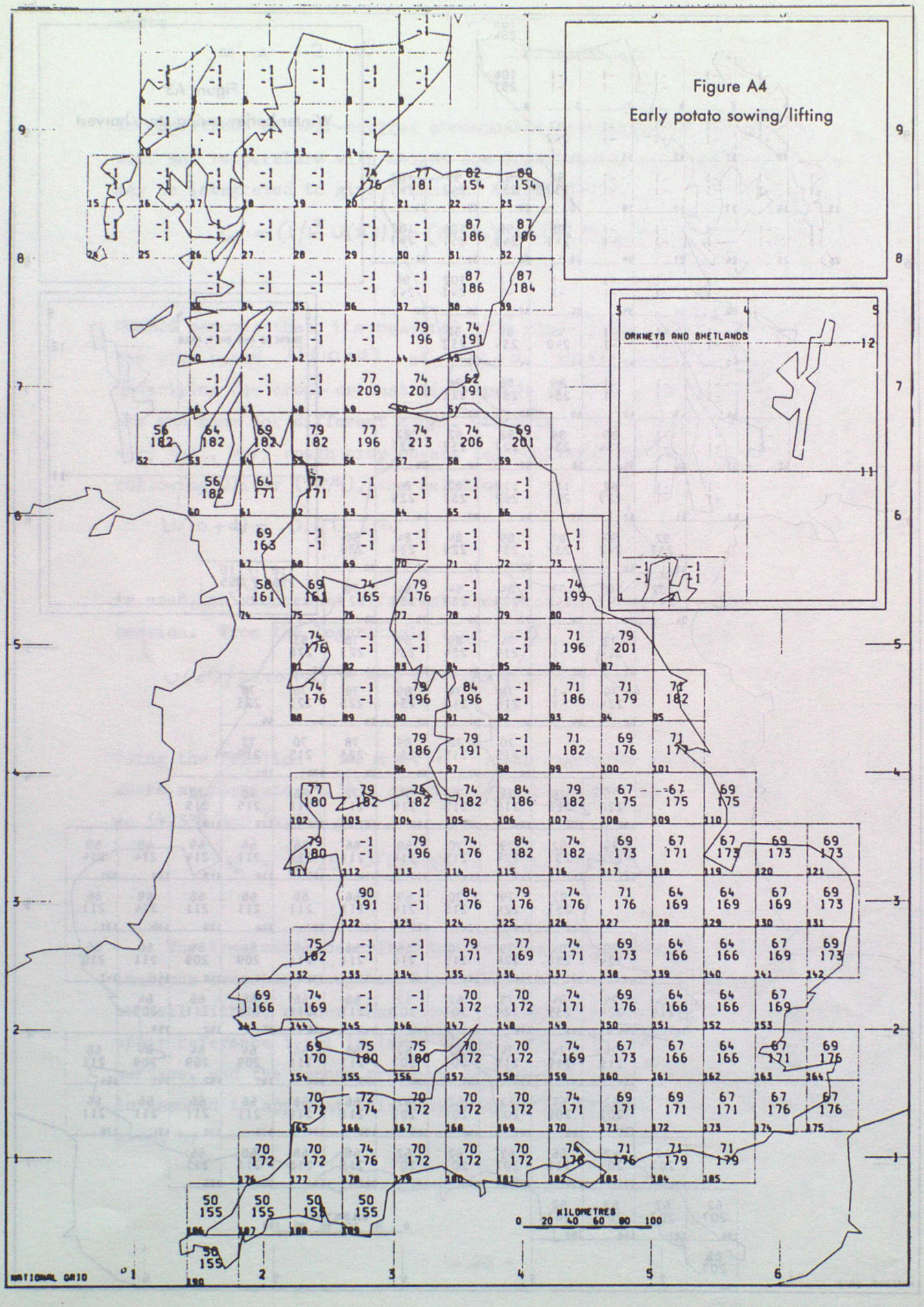


Figure A4
Early potato sowing/lifting
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

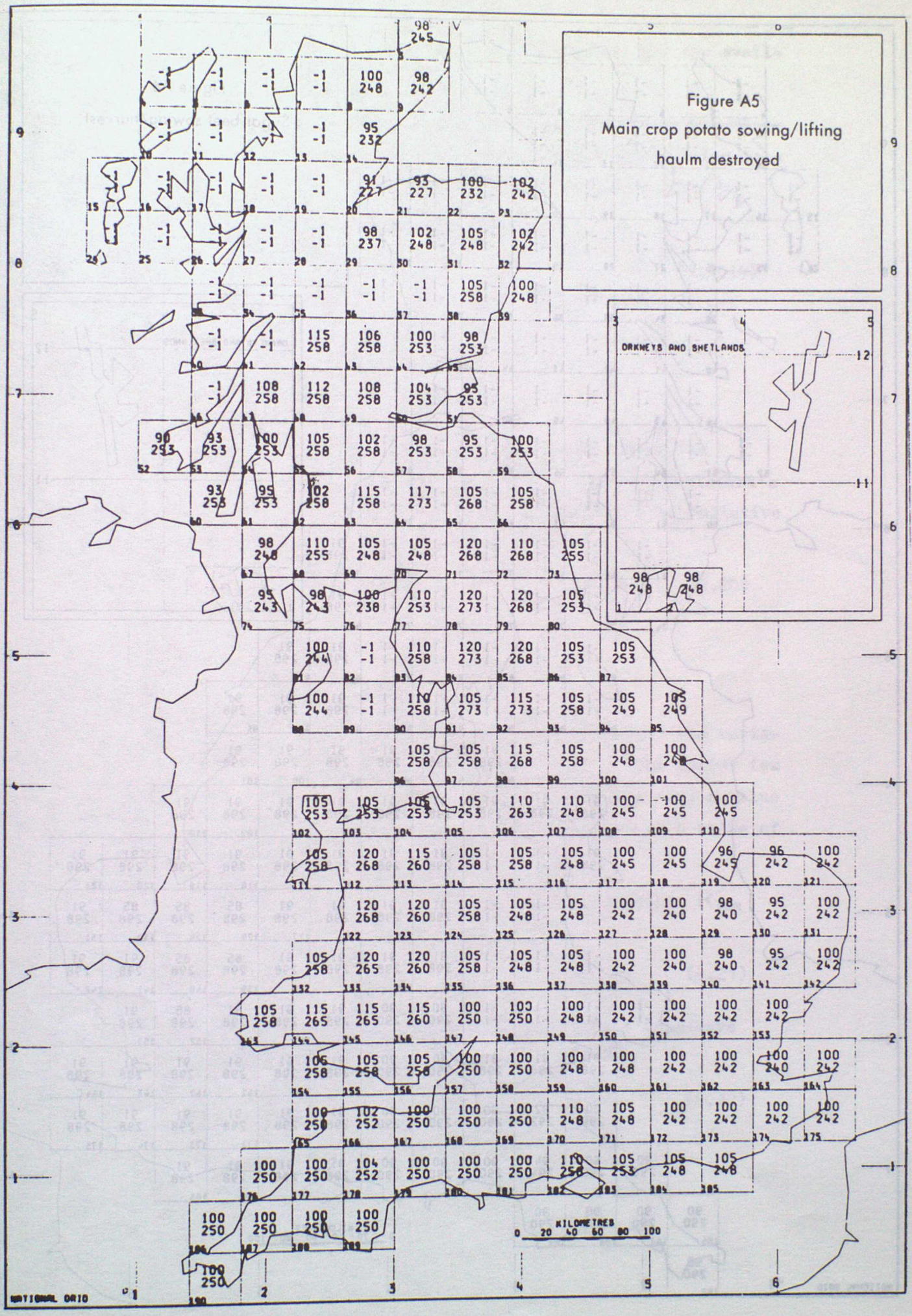


Figure A5
Main crop potato sowing/lifting
haulm destroyed
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

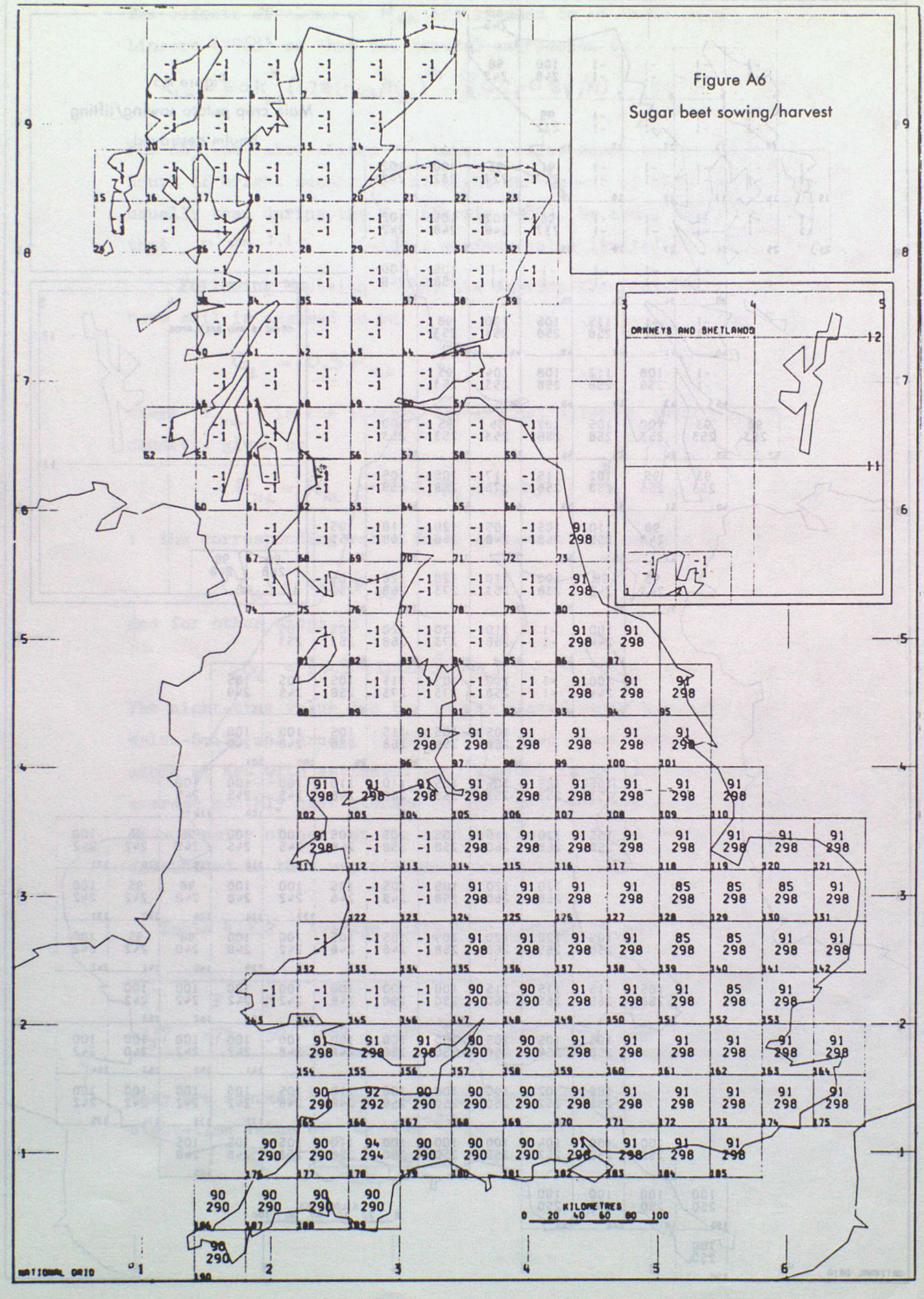


Figure A6
Sugar beet sowing/harvest
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

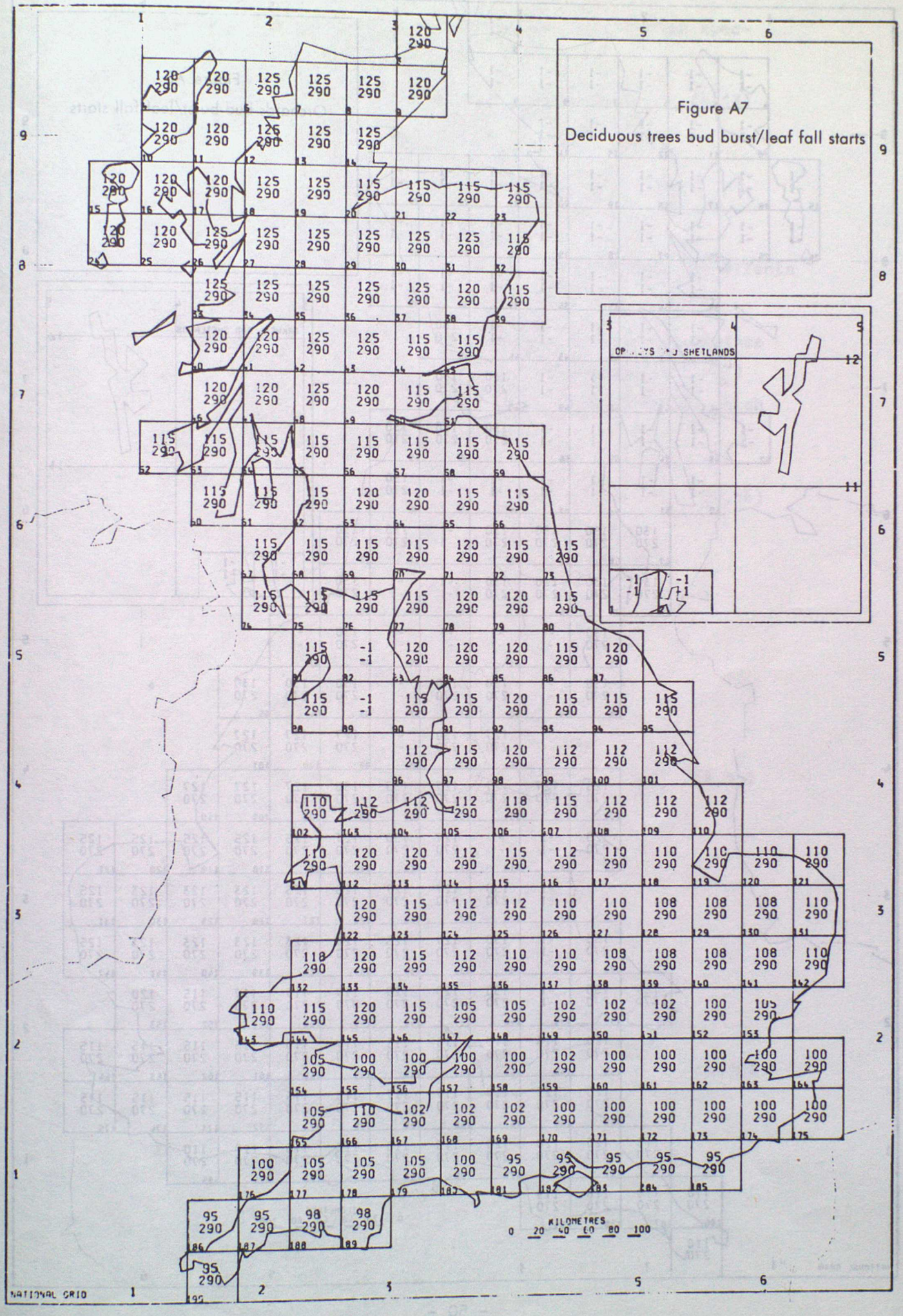


Figure A7
Deciduous trees bud burst/leaf fall starts
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

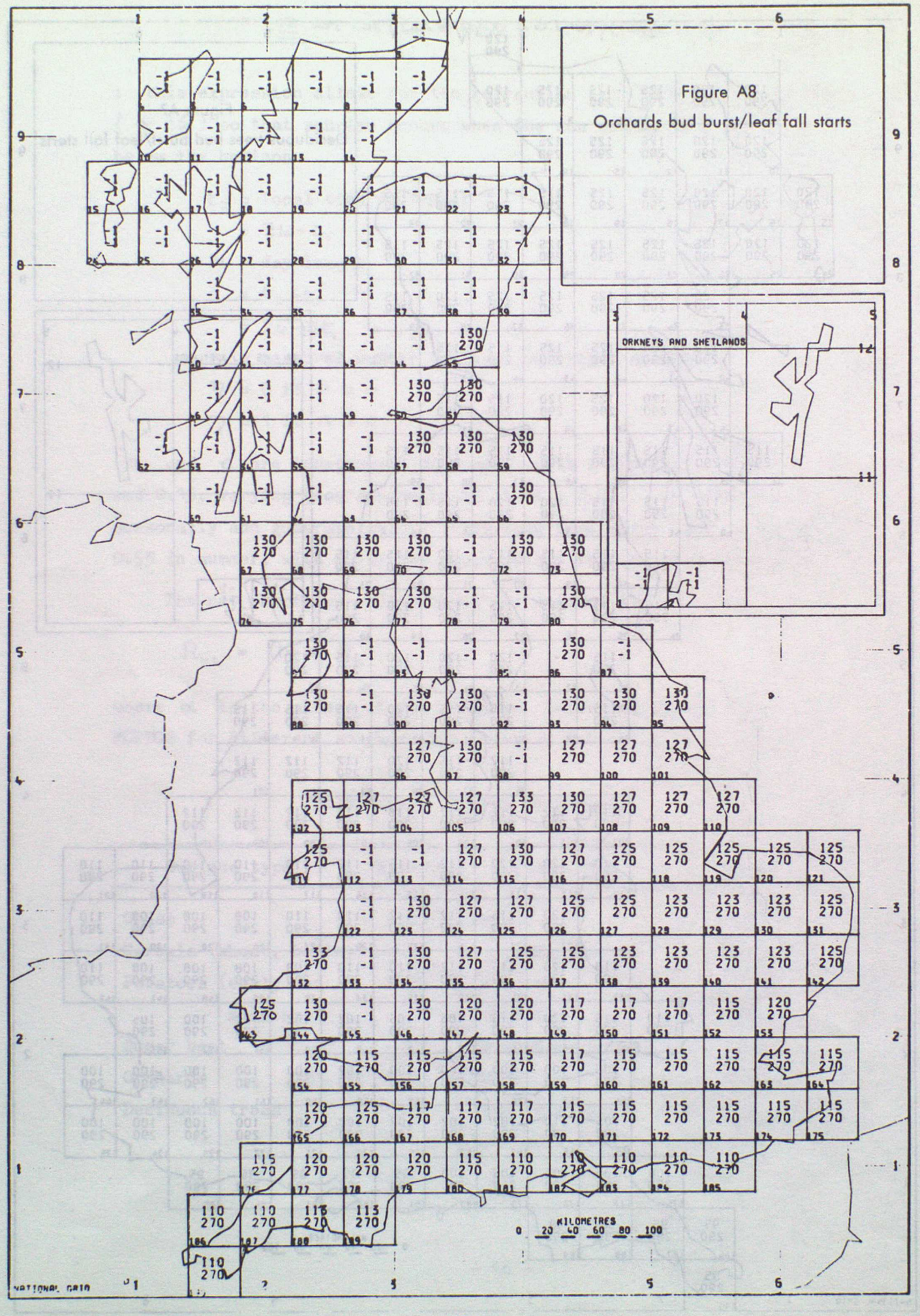


Figure A8
Orchards bud burst/leaf fall starts
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

ANNEXE B Estimates of percentage of land use types in each MORECS square

LAND USE KEY

No	LAND USE
1	URBAN
2	OPEN WATER
3	RIPERIAN
4	ROCK
5	CONIFEROUS WOODLAND
6	HEATHER, GORSE
7	PERMANENT GRASS
8	DECIDUOUS WOODLAND
9	ORCHARDS
10	ROUGH GRAZING
11	CEREALS
12	MAIN CROP POTATOES
13	TEMPORARY GRASS
14	FALLOW, BARE GROUND

SQUARE NO.	PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE													
	LAND USE (SEE KEY)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	3	3	0	5	12	12	0	0	20	13	2	30	0
2	0	0	2	0	5	9	15	0	0	15	16	3	35	0
3	0	2	3	1	5	4	17	0	0	30	15	3	20	0
4	0	3	2	1	2	12	16	0	0	60	2	1	1	0
5	0	3	2	0	2	15	13	0	0	61	2	1	1	0
6	0	3	2	0	2	13	10	0	0	69	0	0	1	0
7	0	3	2	3	6	10	15	0	0	60	0	0	1	0
8	0	3	2	2	8	12	11	0	0	61	0	1	0	0
9	0	2	3	0	5	7	17	0	0	57	4	1	4	0
10	0	3	2	2	2	17	11	0	0	61	1	0	1	0
11	0	0	3	1	2	10	11	0	0	69	2	1	1	0
12	0	5	3	4	8	5	14	0	0	58	1	1	1	0
13	0	3	3	5	10	12	13	0	0	51	1	1	1	0
14	0	0	3	0	7	6	12	0	0	67	0	0	5	0
15	0	3	3	0	2	30	12	0	0	48	0	0	2	0
16	0	0	3	0	8	20	11	0	0	56	0	0	2	0
17	0	0	3	3	8	8	13	0	0	65	0	0	0	0
18	0	3	3	5	8	13	10	0	0	55	2	1	0	0
19	0	3	2	4	12	14	10	0	0	43	8	4	0	0
20	0	0	0	0	21	2	10	0	0	12	27	9	19	0
21	0	0	1	0	12	5	16	1	0	24	24	6	11	0
22	0	0	0	0	10	0	0	2	0	0	42	13	33	0
23	0	1	0	0	10	9	3	1	0	3	40	9	24	0
24	0	3	0	0	10	18	16	0	0	53	0	0	0	0
25	0	0	1	2	10	22	15	0	0	50	0	0	0	0
26	0	0	0	4	8	19	13	0	0	56	0	0	0	0
27	0	3	0	4	10	20	12	0	0	48	2	1	0	0
28	0	8	0	2	15	11	13	0	0	51	0	0	0	0
29	0	3	2	4	16	5	14	0	0	54	2	0	0	0
30	0	0	3	2	15	15	21	1	0	29	12	2	0	0
31	0	0	0	0	10	7	8	1	0	7	37	9	21	0
32	4	0	0	0	8	0	16	1	0	9	34	8	20	0
33	0	8	1	5	3	20	13	0	0	50	0	0	0	0
34	0	4	3	2	10	13	11	0	0	57	0	0	0	0
35	0	5	3	5	12	20	18	0	0	37	0	0	0	0
36	0	0	4	3	11	5	20	1	0	48	4	2	2	0

SQUARE NO.	PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE													
	LAND USE (SEE KEY)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
37	0	0	2	3	15	3	19	1	0	30	15	5	7	0
38	0	0	2	0	16	3	15	1	0	32	17	6	8	0
39	0	0	0	0	7	5	33	1	0	12	24	7	11	0
40	0	2	2	5	15	15	15	2	0	44	0	0	0	0
41	0	2	2	5	15	15	19	2	0	40	0	0	0	0
42	0	2	2	4	10	10	17	2	0	47	3	1	2	0
43	0	2	2	4	10	3	18	1	0	49	6	2	3	0
44	1	0	0	0	10	3	13	1	0	19	29	12	12	0
45	1	0	0	0	8	0	17	1	0	4	39	16	14	0
46	0	0	2	1	9	16	19	2	0	51	0	0	0	0
47	0	2	0	2	20	20	21	2	0	33	0	0	0	0
48	0	4	2	0	18	2	24	1	0	42	3	1	3	0
49	1	2	3	0	6	3	23	1	0	47	7	2	5	0
50	3	2	1	0	6	0	16	1	0	20	29	10	12	0
51	0	0	0	0	3	0	16	1	0	5	48	14	13	0
52	0	2	2	0	8	5	19	2	0	57	5	0	0	0
53	0	0	3	4	10	10	15	2	0	56	0	0	0	0
54	0	0	2	3	12	18	13	2	0	40	0	0	10	0
55	6	0	3	0	5	0	31	1	0	35	9	2	8	0
56	0	0	3	0	8	0	28	1	0	16	23	4	17	0
57	5	1	3	0	5	5	28	1	0	26	14	5	7	0
58	0	0	3	0	5	0	19	1	0	28	24	6	14	0
59	1	0	3	0	8	1	22	5	0	11	27	5	17	0
60	0	0	3	0	10	5	17	2	0	52	5	6	0	0
61	0	0	3	0	10	15	12	2	0	50	2	1	5	0
62	0	0	4	0	10	11	27	1	0	32	5	1	9	0
63	0	0	3	0	8	5	25	1	0	44	4	1	9	0
64	0	0	3	0	12	4	19	1	0	51	3	3	4	0
65	0	0	3	0	10	9	20	1	0	37	10	3	7	0
66	0	0	0	0	7	3	23	4	0	37	12	3	11	0
67	0	0	3	0	10	6	29	1	0	36	5	1	9	0
68	0	1	3	0	10	15	20	1	0	40	4	1	5	0
69	0	0	3	0	10	9	25	1	0	38	5	1	8	0
70	0	0	2	0	7	7	17	1	0	39	9	2	16	0
71	0	0	2	0	10	4	31	2	0	37	6	2	6	0

SQUARE NO.	PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE													
	LAND USE (SEE KEY)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
72	2	0	0	0	10	12	36	4	0	19	7	2	8	0
73	16	0	0	0	0	0	49	4	0	2	6	0	23	0
74	0	0	0	0	9	4	3	1	0	3	0	13	67	0
75	0	1	3	0	9	7	28	1	0	19	0	3	29	0
76	1	0	0	0	10	8	17	1	0	8	0	7	48	0
77	0	1	1	0	5	6	43	0	0	23	0	0	21	0
78	0	1	0	0	5	10	30	3	0	26	0	0	25	0
79	2	0	0	0	5	26	36	2	0	18	4	2	5	0
80	12	0	0	0	4	0	30	4	0	3	28	5	14	0
81	0	0	3	0	3	3	22	3	0	25	9	5	27	0
82														
83	0	1	3	4	6	3	34	2	0	36	3	1	7	0
84	0	0	3	3	2	5	38	1	0	41	3	1	3	0
85	0	0	2	1	3	11	24	2	0	30	17	3	7	0
86	1	0	3	1	4	3	34	2	0	14	23	4	11	0
87	1	0	0	0	9	4	24	1	0	28	21	4	8	0
88	1	0	0	0	5	1	13	1	0	14	14	8	43	0
89														
90	7	0	5	0	7	5	48	2	0	10	8	3	5	0
91	1	1	4	2	2	13	42	2	0	14	10	4	5	0
92	3	0	2	1	2	18	25	2	0	23	15	4	5	0
93	3	0	3	0	4	1	37	1	0	3	30	7	11	0
94	0	0	2	0	9	0	25	1	0	3	41	8	11	0
95	0	0	2	0	2	5	18	1	0	1	50	9	12	0
96	10	1	1	0	1	0	23	2	0	2	22	22	16	0
97	18	0	3	0	3	6	37	2	0	7	12	5	7	0
98	15	0	4	2	4	11	36	1	0	15	7	2	3	0
99	15	1	0	0	4	11	9	1	0	17	26	7	9	0
100	1	1	2	0	2	3	28	2	0	4	38	11	8	0
101	4	0	0	0	2	2	23	2	0	1	42	15	9	0
102	0	0	3	0	3	3	57	2	0	11	7	1	13	0
103	0	0	3	0	7	0	34	2	0	38	4	1	11	0
104	5	0	4	0	2	1	50	2	0	17	6	3	10	0
105	11	0	4	0	5	0	35	4	0	1	19	19	2	0

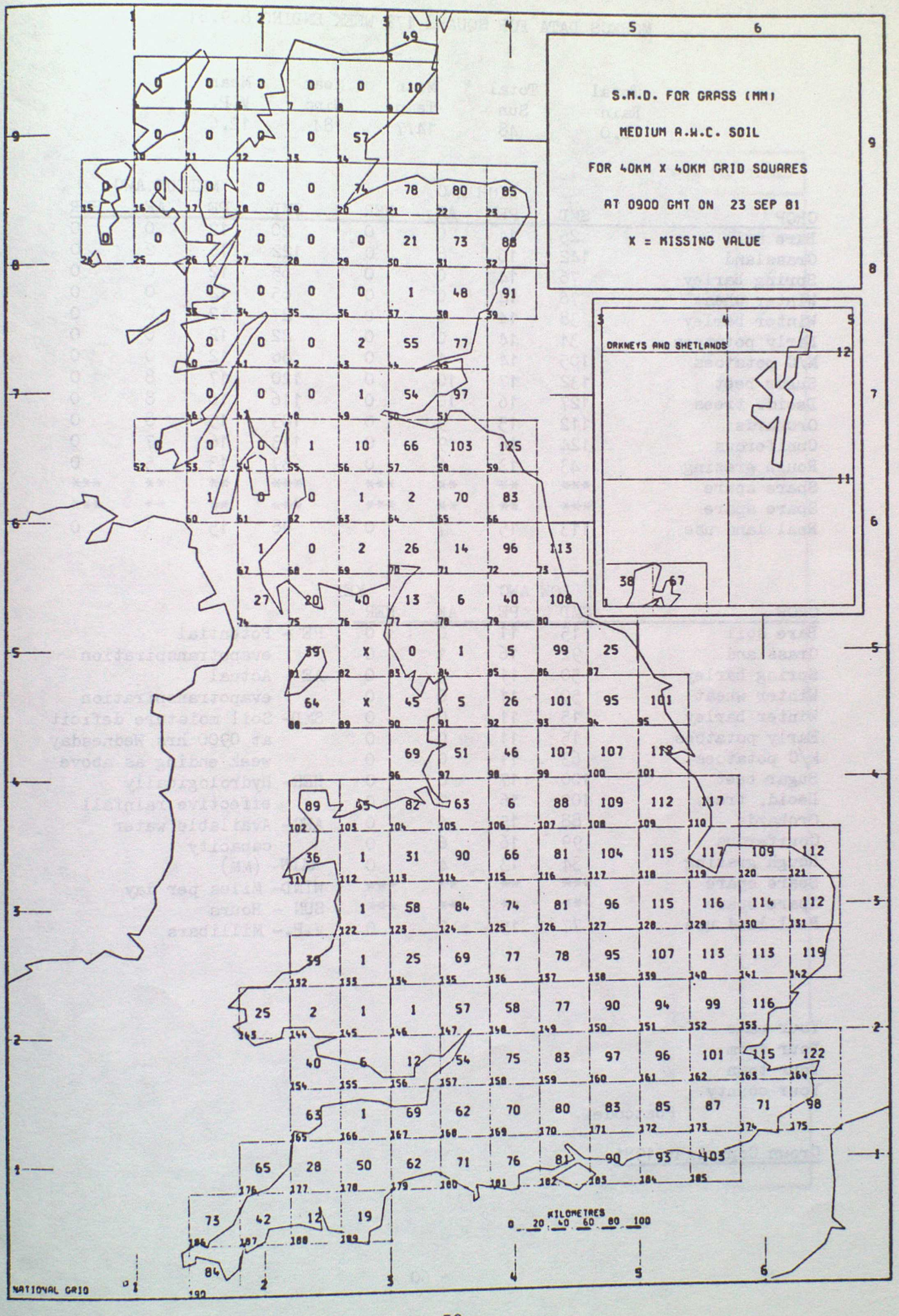
SQUARE NO.	PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE													
	LAND USE (SEE KEY)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
106	8	0	2	1	2	5	47	3	0	17	8	4	3	0
107	13	0	2	0	3	1	33	2	0	17	18	4	7	0
108	1	0	0	0	1	0	30	1	0	4	42	12	9	0
109	0	0	0	0	4	0	30	1	0	0	43	14	8	0
110	2	0	0	0	0	0	31	0	0	2	45	9	11	0
111	0	0	3	0	7	0	37	2	0	40	3	1	7	0
112	0	1	3	2	10	5	31	2	0	38	2	1	5	0
113	1	0	3	2	5	2	39	1	0	25	9	2	11	0
114	1	0	3	0	1	1	47	3	0	6	20	7	11	0
115	2	0	3	0	3	7	50	2	0	4	16	3	10	0
116	11	0	3	0	4	1	38	4	0	7	19	4	9	0
117	1	0	1	0	1	0	31	2	0	2	42	9	11	0
118	1	0	0	0	2	0	11	1	0	0	52	22	11	0
119	0	0	7	0	0	0	13	2	0	0	45	23	10	0
120	0	0	3	0	5	0	5	5	1	0	54	22	5	0
121	0	0	4	0	1	0	12	3	0	0	53	22	5	0
122	0	0	2	5	17	0	22	3	0	40	3	1	7	0
123	0	0	3	1	6	2	47	2	0	15	9	3	12	0
124	8	0	3	0	2	3	34	2	0	6	22	5	15	0
125	14	0	3	0	2	2	41	2	0	5	18	3	10	0
126	9	0	3	0	2	0	46	2	0	3	24	2	9	0
127	1	0	2	0	1	1	30	3	0	2	47	3	10	0
128	1	0	2	0	1	1	15	1	0	2	44	28	5	0
129	0	0	2	0	6	0	11	2	2	0	40	32	5	0
130	0	0	0	0	10	1	16	2	0	5	43	16	7	0
131	2	0	2	0	1	2	15	3	1	3	49	18	4	0
132	0	0	3	1	2	3	44	2	0	24	6	2	13	0
133	0	0	3	1	6	2	37	3	0	32	4	1	11	0
134	0	0	3	0	7	0	46	3	2	19	7	0	13	0
135	1	0	2	0	4	1	40	5	7	4	21	4	11	0
136	1	0	5	0	1	0	42	3	7	2	37	1	1	0
137	2	0	3	0	2	5	41	3	0	1	30	3	10	0
138	2	0	3	0	2	0	35	4	0	0	40	4	10	0
139	1	0	3	0	0	0	28	2	2	0	44	14	6	0

SQUARE NO.	PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE													
	LAND USE (SEE KEY)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
140	1	0	3	0	1	0	15	2	2	3	53	15	5	0
141	1	0	0	0	4	1	16	2	1	2	52	15	6	0
142	0	0	2	0	4	2	16	4	1	2	50	14	5	0
143	0	0	3	0	3	2	54	2	0	13	8	3	12	0
144	1	0	3	0	9	1	52	3	0	14	4	2	11	0
145	2	0	2	1	10	10	40	2	0	24	2	1	6	0
146	5	0	3	2	7	5	33	2	0	30	4	2	7	0
147	4	0	2	0	12	0	38	6	2	0	23	2	11	0
148	2	0	3	0	5	3	49	4	1	3	20	2	8	0
149	1	0	3	0	1	2	33	3	0	1	41	3	12	0
150	1	0	2	0	2	1	45	4	0	1	30	2	12	0
151	3	0	2	0	3	1	30	4	1	1	41	7	7	0
152	1	0	2	0	2	0	27	4	1	0	46	11	6	0
153	2	2	2	0	1	0	26	3	1	0	47	11	5	0
154	1	0	3	0	8	6	39	2	0	23	5	2	11	0
155	12	0	0	2	13	7	27	1	0	28	5	0	5	0
156	13	0	3	1	10	1	47	2	0	9	7	1	6	0
157	10	0	2	1	3	0	46	4	3	3	16	2	10	0
158	0	0	3	0	5	0	50	7	0	5	21	1	8	0
159	0	0	3	0	3	1	26	7	1	6	38	3	12	0
160	4	0	3	0	8	0	26	8	1	3	33	3	11	0
161	25	1	4	0	2	0	50	4	2	1	6	2	3	0
162	19	3	0	0	2	0	23	7	4	0	29	9	4	0
163	2	0	2	0	2	0	28	7	10	2	30	10	7	0
164	2	0	2	0	0	0	23	5	5	0	34	22	7	0
165.	0	0	6	0	4	0	54	4	2	10	7	3	10	0
166	0	0	2	0	4	1	27	4	0	22	17	0	23	0
167	0	0	4	0	3	1	56	3	1	4	11	2	15	0
168	0	1	4	1	4	3	49	5	3	4	10	2	14	0
169	1	0	2	0	2	0	40	4	0	5	33	4	9	0
170	1	0	2	0	5	1	28	8	0	6	33	3	13	0
171	3	0	2	0	8	1	27	12	2	8	22	3	12	0
172	2	0	3	0	6	2	38	13	0	2	18	2	14	0
173	2	0	3	0	4	0	31	12	11	0	21	3	13	0

SQUARE NO.	PERCENTAGES OF LAND USES (1-14) DEVOTED TC EACH SQUARE													
	LAND USE (SEE KEY)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
174	1	0	2	0	3	0	34	14	8	0	22	5	11	0
175	2	0	2	0	2	0	24	8	0	5	34	11	12	0
176	0	0	5	0	0	0	63	5	0	17	0	5	5	0
177	0	0	5	0	3	3	62	2	1	7	7	0	10	0
178	1	0	3	0	5	0	38	6	2	12	13	2	18	0
179	1	0	5	0	4	0	60	4	2	5	7	1	11	0
180	0	0	2	0	4	7	35	2	0	6	15	6	23	0
181	1	0	0	0	4	11	23	3	0	2	36	10	10	0
182	2	0	1	0	15	0	21	14	0	10	23	4	10	0
183	7	0	1	0	6	1	18	11	0	8	30	5	13	0
184	3	0	3	0	2	0	31	6	1	10	25	3	16	0
185	2	0	2	0	4	0	40	8	1	8	18	2	15	0
186	2	0	4	6	2	1	45	10	0	10	0	10	10	0
187	1	0	4	6	2	2	54	4	0	5	0	11	11	0
188	2	3	4	0	3	4	56	3	0	10	0	8	7	0
189	2	0	3	0	3	0	30	5	0	18	15	0	24	0
190	2	0	3	0	0	0	44	6	0	20	0	17	8	0

PE's for impervious urban land use are calculated using a maximum available daily moisture of 0.5 mm. AE is set equal to PE when R $\geq$ PE, or to R (R < PE). Run-off for bare rock is assumed to be so rapid that PE is ignored (with AE=0), so that HER = rainfall.

Annexe C Examples of MORECS outputs


S.M.D. FOR GRASS (MM)
MEDIUM A.W.C. SOIL
FOR 40KM X 40KM GRID SQUARES
AT 0900 GMT ON 23 SEP 81
X = MISSING VALUE
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

MORECS DATA FOR SQUARE 172 WEEK ENDING 8.9.81

Total Rain	Total Sun	Mean Temp	Mean Wind	Mean V.P.
0.0	48	14.7	84	12.6

	HIGH AWC				MEDIUM AWC		
CROP	SMD	PE	AE	HER	SMD	PE	AE	HER
Bare soil	25	14	0	0	20	12	0	0
Grassland	142	16	8	0	122	16	2	0
Spring barley	76	14	0	0	65	12	0	0
Winter wheat	76	14	0	0	65	12	0	0
Winter barley	38	14	0	0	27	12	0	0
Early potatoes	34	14	0	0	22	12	0	0
M/C potatoes	105	14	1	0	86	12	0	0
Sugar beet	132	17	10	0	120	17	8	0
Decid. trees	127	16	10	0	116	16	8	0
Orchards	112	15	9	0	103	15	8	0
Coniferous	124	16	9	0	113	16	7	0
Rough grazing	43	13	6	0	39	13	5	0
Spare spare	***	**	**	***	***	**	**	***
Spare spare	***	**	**	***	***	**	**	***
Real land use	113	15	7	0	98	15	3	0

	LOW AWC			
CROP	SMD	PE	AE	HER
Bare soil	15	11	0	0
Grassland	92	16	1	0
Spring barley	50	11	0	0
Winter wheat	50	11	0	0
Winter barley	15	11	0	0
Early potatoes	15	11	0	0
M/C potatoes	63	11	0	0
Sugar beet	100	17	6	0
Decid. trees	102	16	7	0
Orchards	88	15	6	0
Coniferous	99	16	6	0
Rough grazing	34	13	4	0
Spare spare	***	**	**	***
Spare spare	***	**	**	***
Real land use	77	15	2	0

KEY

PE - Potential evapotranspiration

AE - Actual evapotranspiration

SMD- Soil moisture deficit at 0900 hrs Wednesday week ending as above

HER- Hydrologically effective rainfall

AWC- Available water capacity

RAIN- (MM)

WIND- Miles per day

SUN - Hours

V.P.- Millibars

Your name
Your farm
Your town
Your county
Postcode

Crown Copyright 1981

MORECS DATA FOR WEEK ENDING 22 9 81

UNITS SUN,HRS WIND,MILES PER DAY TEMP,DEG C VP,MBARS ***,NO CROP GROWN SOIL,MEDIUM A.W.C.

	BARE SOIL			GRASS			SP.BARLEY			WIN.WHEAT			M/C POTATO			SUGAR BEET			ORCHARDS			TOT	TOT	MEAN	MEAN	MEAN
SQ	SMD	PE	AE	SMD	PE	AE	SMD	PE	AE	SMD	PE	AE	SMD	PE	AE	SMD	PE	AE	SMD	PE	AE	RAIN	SUN	WIND	TEMP	VP
71	0	9	9	14	15	15	0	9	9	0	9	9	12	17	17	***	**	**	***	**	**	48	31	254	12.2	11.9
72	3	10	10	96	16	16	56	10	10	58	10	10	66	18	18	***	**	**	67	16	16	25	32	272	12.8	11.8
73	5	11	11	113	18	17	88	11	11	90	11	11	70	11	11	115	19	18	98	17	16	19	39	319	13.6	11.9
74	2	10	10	27	16	16	2	10	10	1	11	11	2	10	10	***	**	**	4	16	16	45	33	404	13.1	12.9
75	4	9	9	20	15	15	4	9	9	2	10	10	4	9	9	***	**	**	5	15	15	50	36	336	12.9	12.8
76	3	10	10	40	16	16	3	10	10	15	12	12	12	10	10	***	**	**	17	16	16	48	36	300	12.8	12.5
77	1	10	10	13	15	15	1	10	10	1	10	10	8	10	10	***	**	**	3	16	16	23	36	261	12.9	12.4
78	0	9	9	6	16	16	0	9	9	0	11	11	6	18	17	***	**	**	***	**	**	46	32	265	12.0	11.7
79	1	9	9	40	16	16	3	9	9	10	11	11	26	18	18	***	**	**	***	**	**	34	33	276	12.0	11.4
80	5	11	11	107	17	17	80	11	11	84	11	11	63	11	11	104	18	18	90	17	16	22	39	302	13.4	11.9
81	4	10	10	39	15	15	4	10	10	4	10	10	14	10	10	***	**	**	8	15	15	43	40	344	12.8	12.5
82	***	**	**	***	**	**	***	**	**	***	**	**	***	**	**	***	**	**	***	**	**	***	**	***	****	****
83	0	10	10	0	16	16	0	10	10	0	10	10	0	10	10	***	**	**	***	**	**	77	31	283	12.5	12.0
84	0	9	9	1	16	16	0	9	9	0	9	9	2	18	18	***	**	**	***	**	**	61	28	294	12.1	11.7
85	2	10	10	5	15	15	2	10	10	2	10	10	6	17	17	***	**	**	***	**	**	44	31	295	11.8	11.3
86	5	11	11	98	17	16	58	11	11	71	11	11	54	11	11	95	18	17	83	16	16	26	37	296	13.1	11.8
87	4	10	10	25	16	16	4	10	10	4	10	10	10	10	10	26	17	17	***	**	**	39	38	322	12.7	12.1
88	4	10	10	64	16	16	7	10	10	17	10	10	35	10	10	***	**	**	35	16	16	39	40	335	13.1	12.6
89	***	**	**	***	**	**	***	**	**	***	**	**	***	**	**	***	**	**	***	**	**	***	**	***	****	****
90	3	11	11	44	18	18	3	11	11	3	11	11	27	11	11	***	**	**	18	18	18	38	37	329	13.7	12.8
91	2	10	10	5	16	16	2	10	10	2	10	10	6	19	19	***	**	**	4	17	17	48	30	315	13.0	12.1
92	2	10	10	26	16	16	2	10	10	2	10	10	9	18	18	***	**	**	***	**	**	46	29	313	12.2	11.5
93	4	11	11	101	17	16	50	11	11	66	11	11	62	11	11	98	18	17	82	16	15	27	34	309	13.3	12.1
94	4	11	11	95	17	16	36	11	11	50	11	11	49	11	11	79	18	17	63	16	16	30	34	329	13.5	12.4
95	5	11	11	101	17	16	53	11	11	65	11	11	56	11	11	93	18	17	77	16	16	27	34	328	13.6	12.5
96	3	11	11	69	18	17	3	11	11	7	11	11	47	11	11	64	18	18	38	17	17	31	37	306	14.1	13.4
97	2	11	11	51	17	17	2	11	11	2	11	11	34	11	11	49	18	18	26	18	17	39	33	312	13.6	12.5
98	2	10	10	46	15	15	2	10	10	2	10	10	25	17	17	40	16	16	***	**	**	41	29	329	12.2	11.7
99	4	11	11	106	16	16	54	11	11	74	11	11	67	11	11	111	17	17	94	16	15	24	31	306	13.5	12.4
100	4	11	11	107	16	16	61	11	11	62	11	11	60	11	11	114	17	17	97	16	16	22	32	295	14.0	12.9
101	5	11	11	112	17	17	76	11	11	81	11	11	65	11	11	122	19	18	107	17	16	22	33	353	14.1	12.9
102	2	11	11	89	20	20	38	11	11	44	11	11	43	11	11	81	20	20	58	19	19	42	44	427	14.1	13.3
103	1	9	9	45	16	15	1	9	9	1	9	9	21	9	9	40	16	16	20	16	16	44	36	315	12.8	13.0
104	1	10	10	82	15	15	32	10	10	32	10	10	50	10	10	73	15	15	56	15	15	32	35	269	13.0	13.2
105	1	10	10	63	15	15	1	10	10	2	10	10	29	10	10	55	16	16	36	15	15	30	31	275	13.0	12.6

Annexe D Comparison of MORECS and neutron probe data

The following 10 diagrams show comparisons between MORECS estimates of soil moisture deficit and values deduced from neutron probe measurements.

Certain qualifications of the meteorological data which were used, and of certain of the probe data, are required:

(i) Case 4 (Table 4.6.1): the initial SMD (neutron probe) was assumed to be 33 mm (P E Francis, personal communication)

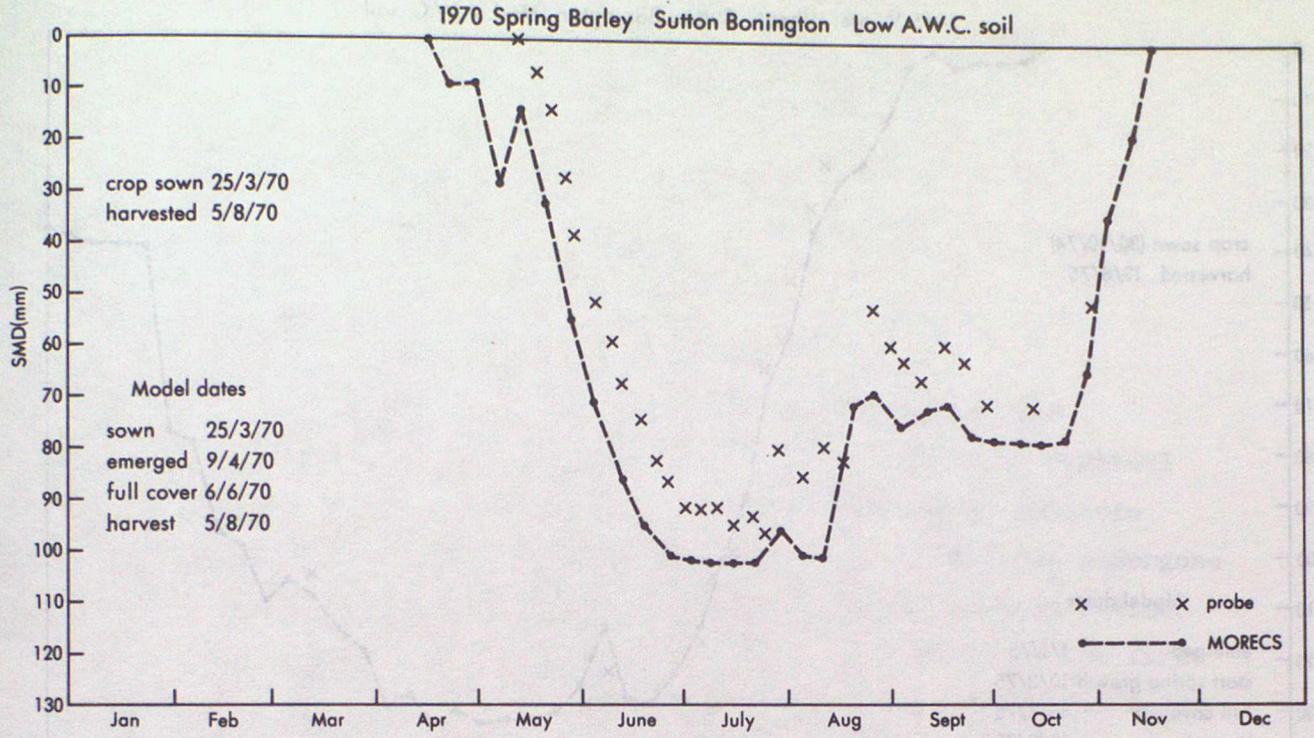
(ii) Cases 5 and 8: Broom's Barn has a very high available water content: it has been set equal to 210 mm here

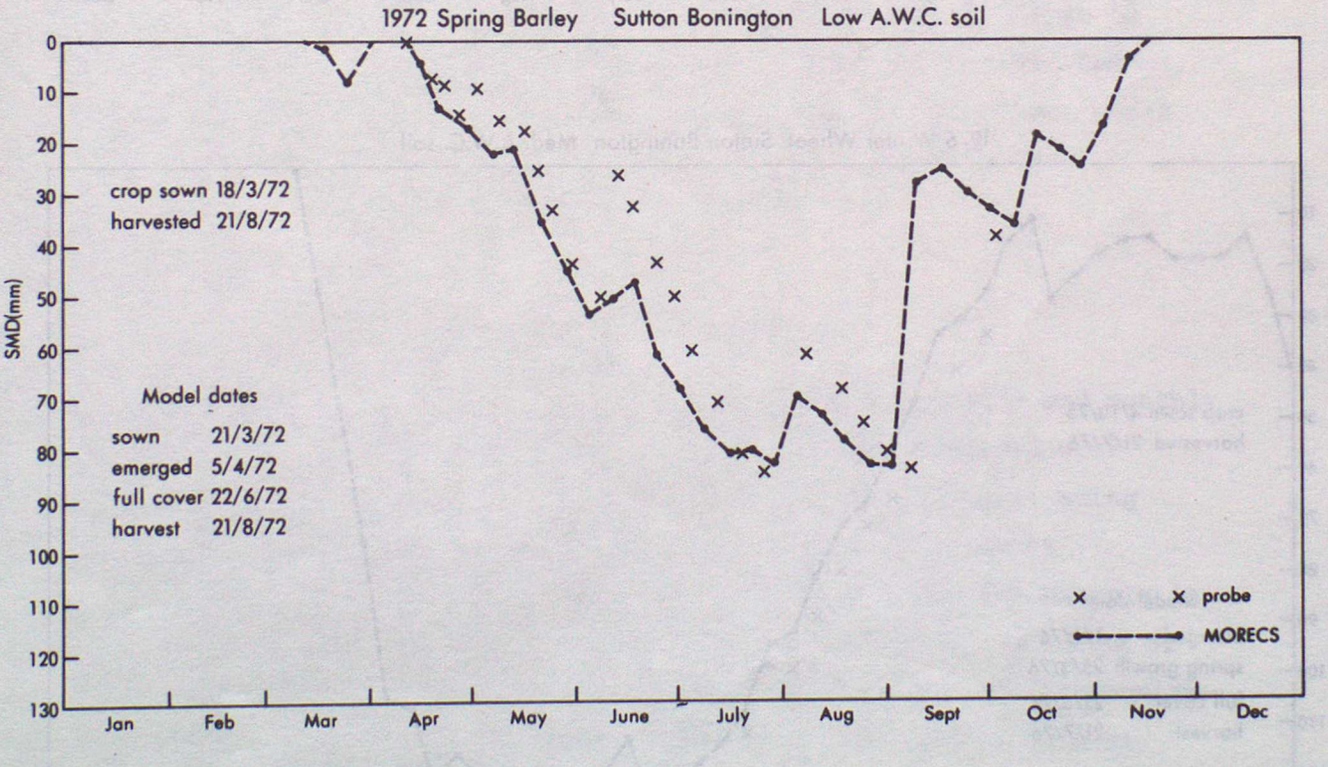
(iii) Case 6: The meteorological data were from Long Ashton. Filton rainfall was taken for 4-17 June, 28 June and 16 August - 1st September

(iv) Case 7: The probe site was 30 km southeast of Finningley. References to rainfall stations nearer the probe site suggested that significant adjustments were required to the Finningley rainfall on several days:

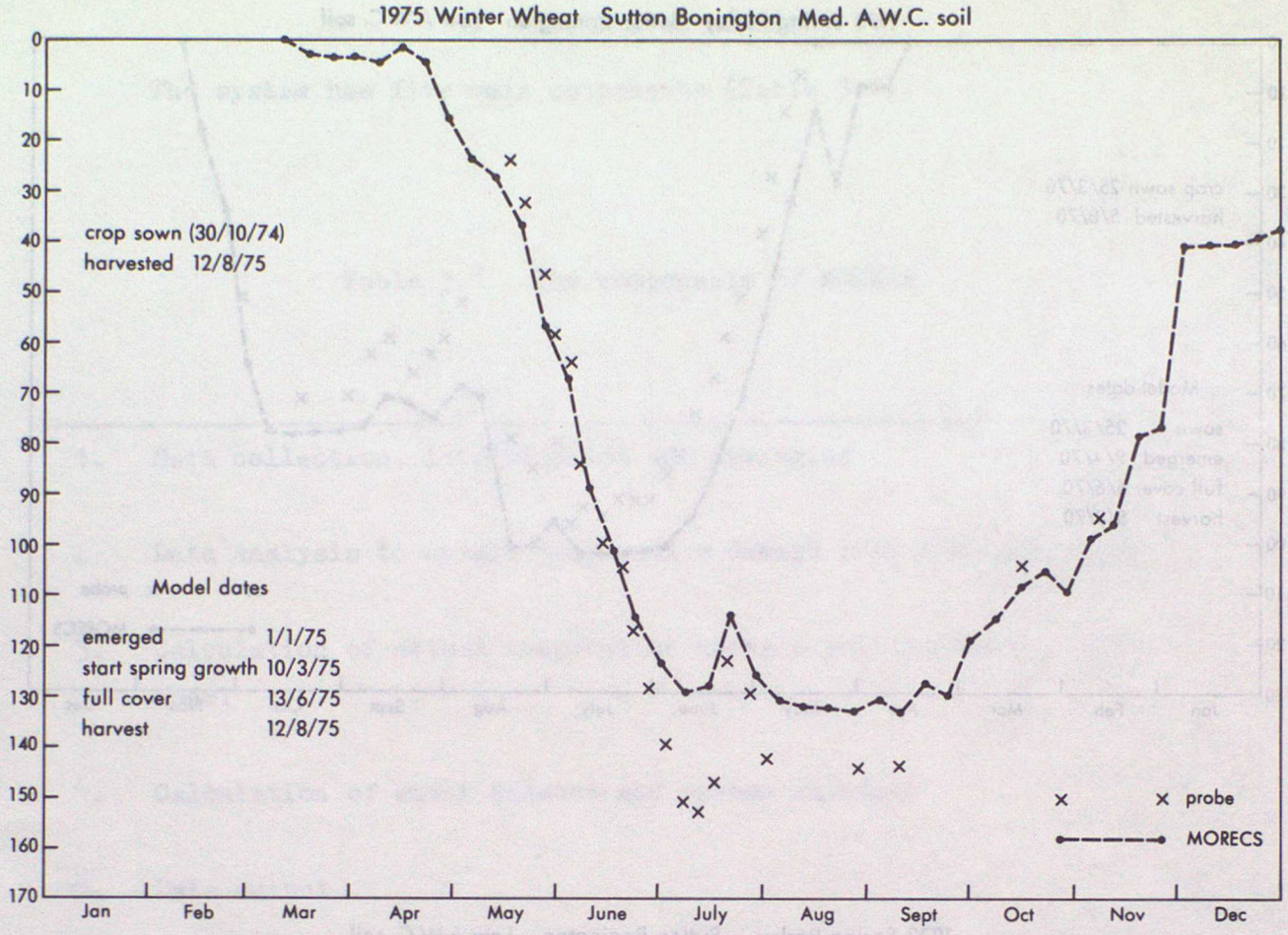
Date	Finningley rainfall (mm)	Estimated MORECS rainfall (mm)
15 June	12.2	6
16 June	8.9	4
1 July	2.8	6
22 July	2.3	5

(v) Case 10: SMD was reset from 12 mm to 0 mm on 12 June.

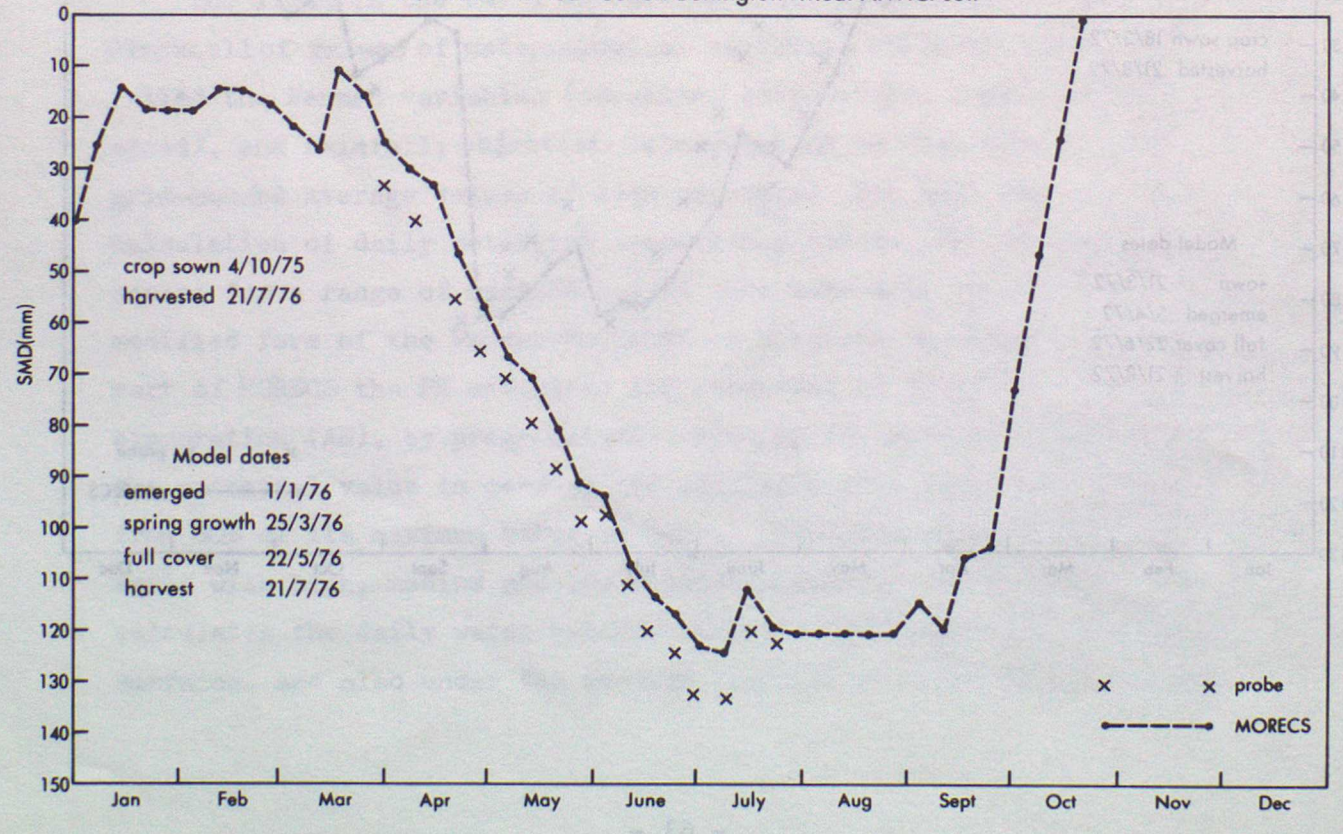

1970 Spring Barley Sutton Bonington Low A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
crop sown 25/3/70
harvested 5/8/70
Model dates
sown 25/3/70
emerged 9/4/70
full cover 6/6/70
harvest 5/8/70
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

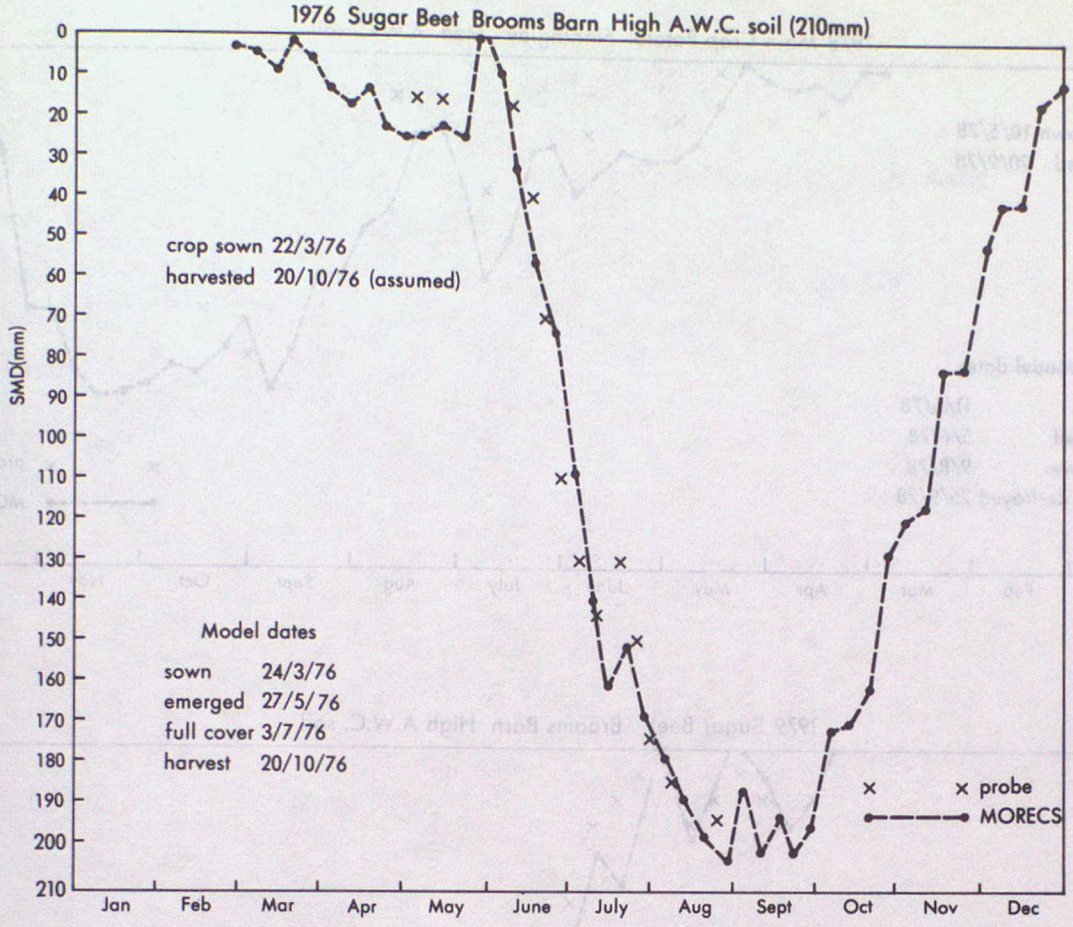

1972 Spring Barley Sutton Bonington Low A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
crop sown 18/3/72
harvested 21/8/72
Model dates
sown 21/3/72
emerged 5/4/72
full cover 22/6/72
harvest 21/8/72
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

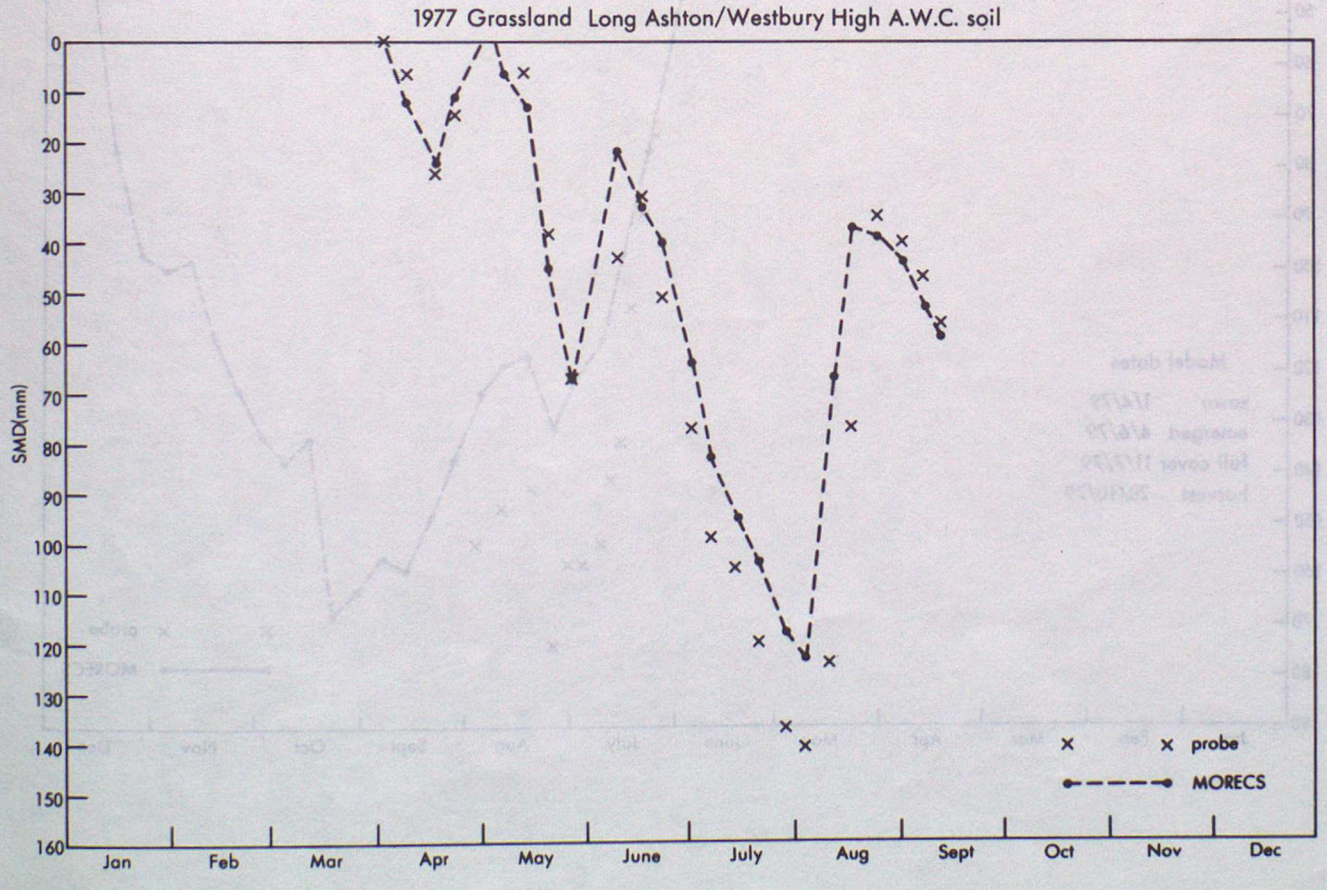
1975 Winter Wheat Sutton Bonington Med. A.W.C. soil

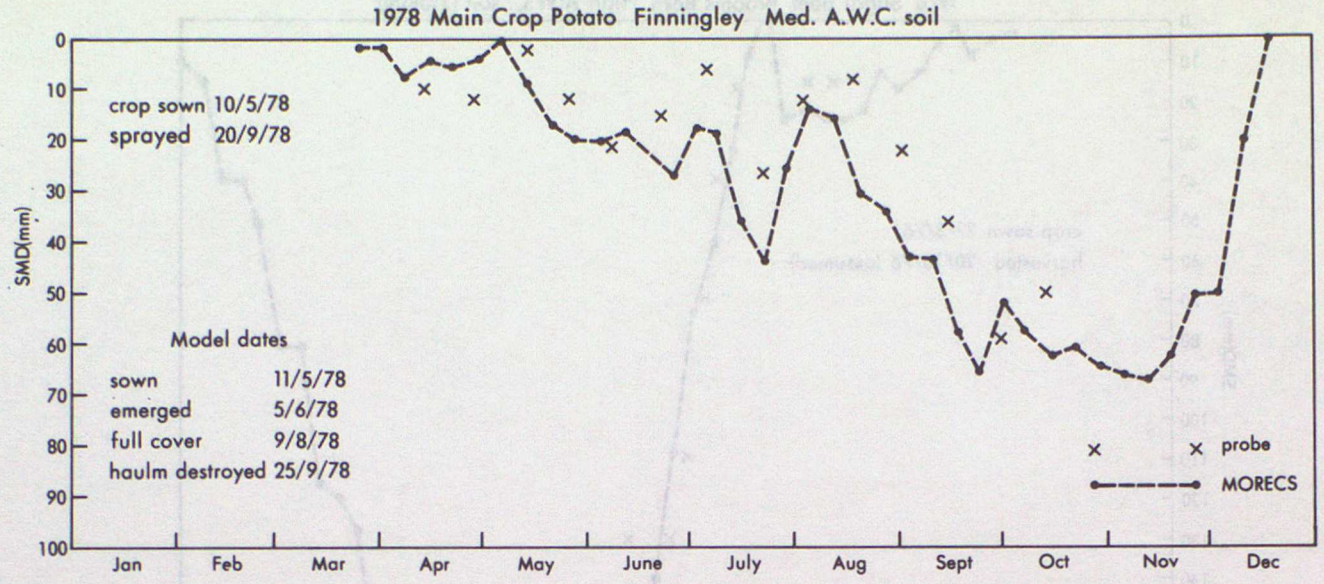


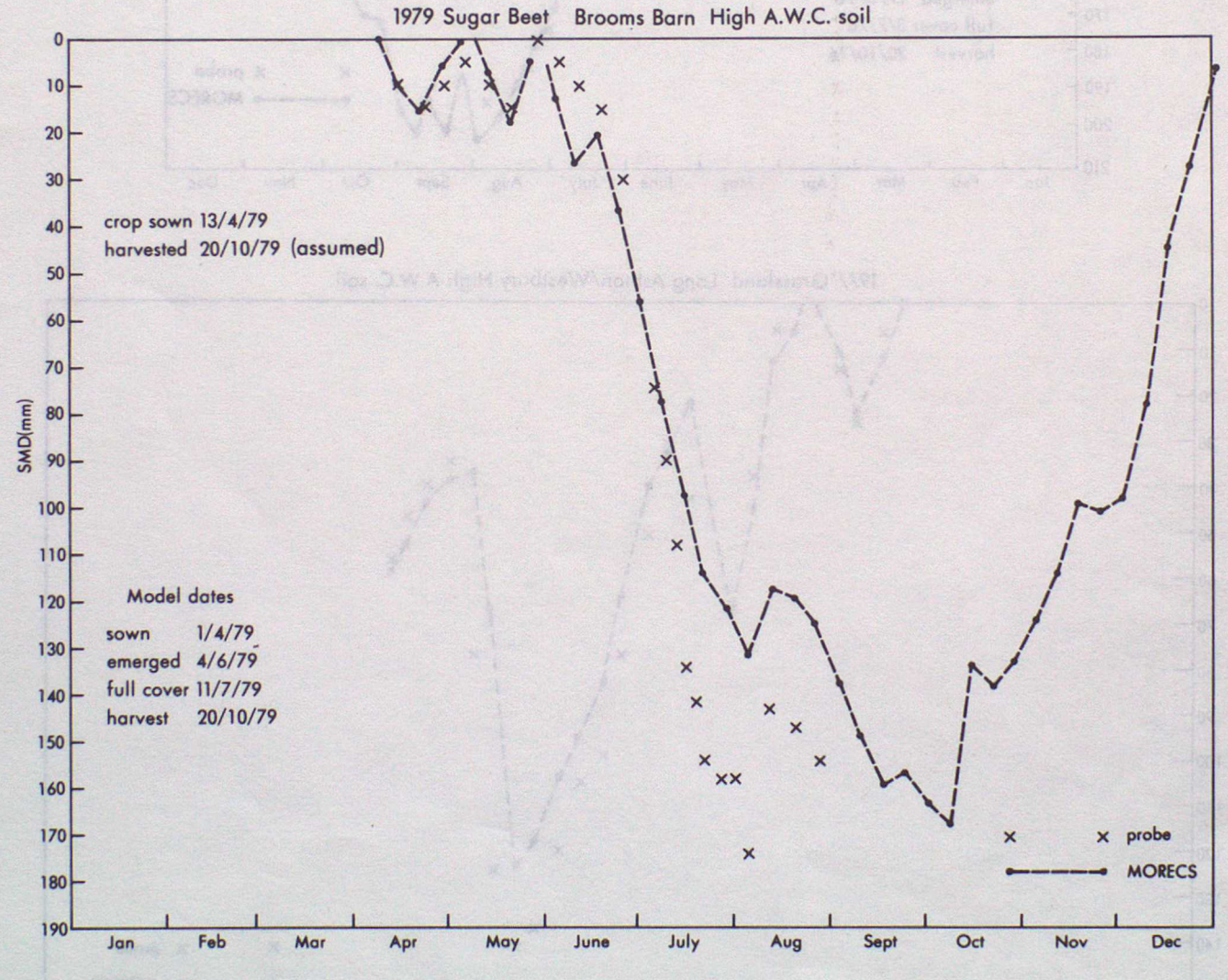
1976 Winter Wheat Sutton Bonington Med. A.W.C. soil

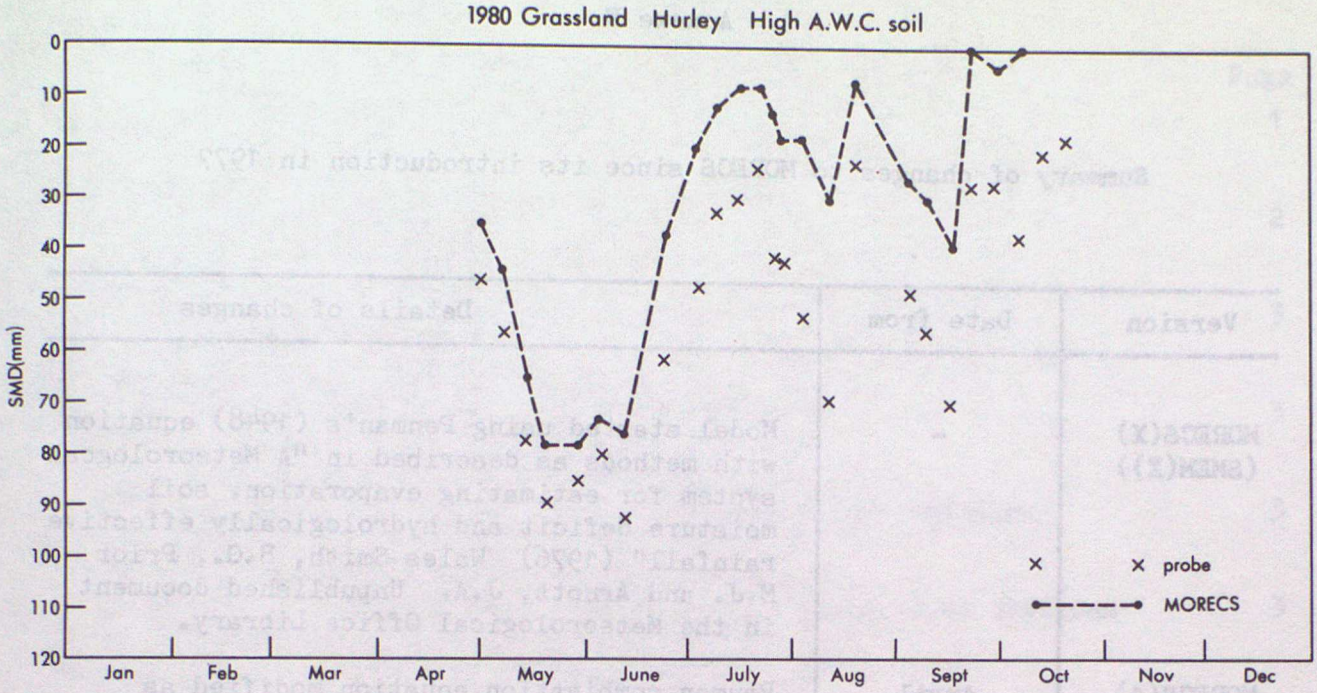


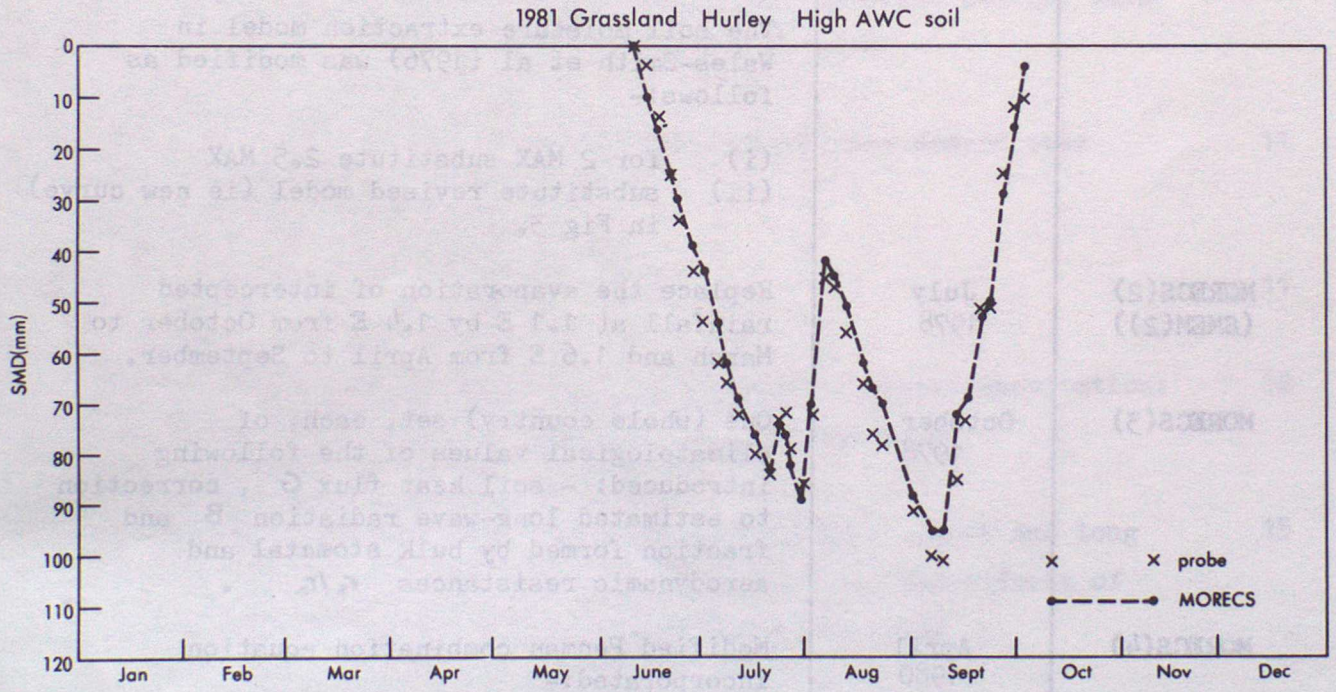

1976 Sugar Beet Brooms Barn High A.W.C. soil (210mm)
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
crop sown 22/3/76
harvested 20/10/76 (assumed)
Model dates
sown 24/3/76
emerged 27/5/76
full cover 3/7/76
harvest 20/10/76
× probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec


1977 Grassland Long Ashton/Westbury High A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
× probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec


1978 Main Crop Potato Finningley Med. A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
crop sown 10/5/78
sprayed 20/9/78
Model dates
sown 11/5/78
emerged 5/6/78
full cover 9/8/78
haulm destroyed 25/9/78
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec


1979 Sugar Beet Brooms Barn High A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
crop sown 13/4/79
harvested 20/10/79 (assumed)
Model dates
sown 1/4/79
emerged 4/6/79
full cover 11/7/79
harvest 20/10/79
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec


1980 Grassland Hurley High A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
probe
MORECS


1981 Grassland Hurley High AWC soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
probe
MORECS

Annexe E

Summary of changes to MORECS since its introduction in 1977

Version	Date from	Details of changes
MORECS(X) (SMEM(X))	-	Model started using Penman's (1948) equation with methods as described in "A Meteorologcal system for estimating evaporation, soil moisture deficit and hydrologically effective rainfall" (1976) Wales-Smith, B.G., Prior M.J. and Arnott, J.A. Unpublished document in the Meteorological Office Library.
MORECS(1) (SMEM(1))	April 1978	Penman combination equation modified as follows:- for $\frac{\Delta}{\Delta+\gamma}$ and $\frac{\gamma}{\Delta+\gamma}$ substitute $\frac{\Delta}{\Delta+2.4\gamma}$ and $\frac{2.5\gamma}{\Delta+2.4\gamma}$ and for $a+bn/N$ substitute $\delta(a+bn/N)+(1-\delta)c$ The soil moisture extraction model in Wales-Smith et al (1976) was modified as follows:- (i) for 2 MAX substitute 2.5 MAX (ii) substitute revised model (ie new curve) in Fig 3.
MORECS(2) (SMEM(2))	July 1978	Replace the evaporation of intercepted rainfall at 1.1 E by 1.4 E from October to March and 1.6 E from April to September.
MORECS(3)	October 1978	One (whole country) set, each, of climatological values of the following introduced: - soil heat flux G , correction to estimated long-wave radiation B and fraction formed by bulk stomatal and aerodynamic resistances r_s/r_a .
MORECS(4)	April 1980	Modified Penman combination equation incorporated:- $E_t = \frac{\Delta(R_N-G)+0.17\times2.5\,(1+0.54U)(e_s-e)}{\Delta+\gamma\,(1+2.5r_s(1+0.54U)/250)}$
MORECS(5)	April 1981	Revised (larger) values of r_s introduced.
MORECS(6)	May 1981	Whole MORECS system revised. Write-up of the new system produced in July 1981

Version	Date from	Details of changes
MORECS (7)	March 1982	Revised surface resistance and leaf area index values for grass land. Amended crop development dates for areas in Wales and the South West (figs. A1 to A6)